



This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

### Usage guidelines

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

- + *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.
- + *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.
- + *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.
- + *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

### About Google Book Search

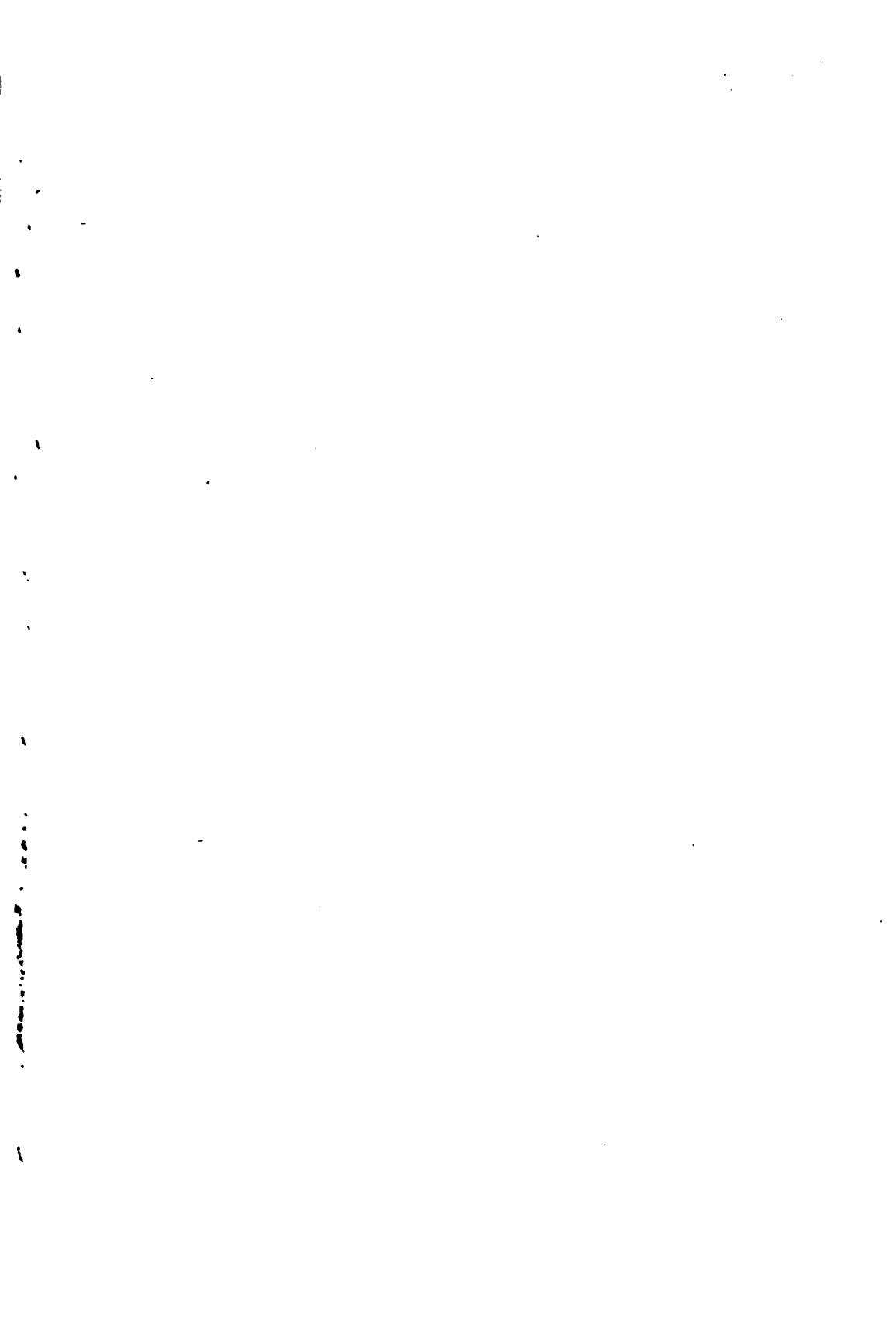
Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at <http://books.google.com/>

APR 30 1907

Mining dept.

LIBRARY  
OF THE  
UNIVERSITY OF CALIFORNIA.

*Class*











# **INDUSTRIAL FURNACES AND METHODS OF CONTROL**

**BY**

**EMILIO DAMOUR**

**Ingenieur Civil des Mines**

**Authorized Translation with Additions**

**by**

**A. L. J. QUENEAU, B.S. (Paris), E.M., A.M. (Columbia)**

**Consulting Engineer, The New Jersey Zinc Company**

---

**FIRST EDITION**



**New York and London**

**THE ENGINEERING AND MINING JOURNAL**

**1906**

TN 347  
T 2  
MINING DEPT.

*McC*  
COPYRIGHT 1906

BY

THE ENGINEERING AND MINING JOURNAL

Also Entered at

STATIONERS' HALL COURT, LONDON, ENGLAND

---

*All Rights Reserved*

## LIST OF ILLUSTRATIONS.

---

- Fig. 1. Graphic Method for the Determination of the Temperature of Combustion.
- Fig. 2. Temperature of Combustion of Hydrogen in Air.
- Fig. 3. Temperature of Combustion of Carbon Monoxide in Air.
- Fig. 4. Temperature of Combustion of Water Gas ( $\text{CO} + \text{H}_2$ ) in Air.
- Fig. 5. Temperature of Combustion of Carbon in Air.
- Fig. 6. Temperature of Combustion of Siemens Gas ( $\text{CO} + 2\text{N}_2$ ).
- Fig. 7. Temperature of Combustion of Pittsburg Natural Gas.  
(a) Combustion with no Excess of Air.  
(b) Combustion with 25% Excess of Air.
- Fig. 8. Temperature of Combustion of Iola Natural Gas, with no Excess of Air.
- Fig. 9. Temperature of Combustion of Iola Natural Gas, with 25% Excess of Air.
- Fig. 10. Temperature of Combustion of Iola Natural Gas, with 5% of Gas Unburned.
- Fig. 11. Curve of the Dissociation of Carbon Dioxide,  $\text{CO}_2$ .
- Fig. 12. Curve of the Dissociation of Carbon Monoxide,  $\text{CO}$ .
- Fig. 13. Siemens Gas Producer with Siphon.
- Fig. 14. Taylor Gas Producer with Mechanical Feed.
- Fig. 15. Morgan Gas Producer with Mechanical Feed.
- Fig. 16. Ebelsmen Gas Producer.
- Fig. 17. New Siemens Furnace with Horseshoe Hearth.
- Fig. 18. Water-Sealed Taylor Gas-Producer with Bild Automatic Feed.
- Fig. 19. Dellwick-Fleischer Water Gas-Producer.
- Fig. 20. Swindell Gas-Producer with Double Face.
- Fig. 21. Duff Gas-Producer.
- Fig. 22. Boëtius Furnace.
- Fig. 23. Curves Showing the Percentages of the Heat Utilized and Lost in Direct-Fired Furnaces.

- Fig. 24. Puddling Furnace of the Forges d'Eurville.
- Fig. 25. Section through a Belleville Boiler and Economizer.
- Fig. 26. Longitudinal Section and Front Elevation of a Belleville Boiler and Economizer.
- Fig. 27. Section of the Niclausse Multitubular Boiler.
- Fig. 28. Front Elevation of a Niclausse Multitubular Boiler.
- Fig. 29. Curves Showing the Percentages of the Heat Lost and Utilized in Multitubular Boilers.
- Fig. 30. Curve Showing the Theoretical Temperatures of Formation of Siemens Gas, the Primary Air Being Injected at 0°, 600°, 800°, 1000°, 1500° C.
- Fig. 31. Illuminating Gas Muffle Furnace of the Compagnie Parisienne du Gaz.
- Fig. 32. Illuminating Gas Muffle Furnace of the Compagnie Parisienne du Gaz.
- Fig. 33. Glass Tank Furnace Fired with Siemens Gas, with Recuperators of the Lencauchez Parallel Counter-Current Type.
- Fig. 34. Graphic Determination of the Temperature of Combustion of Siemens Gas ( $\text{CO} + 2\text{N}_2$ ), Heated to 1290° C., the Secondary Air Being Pre-heated to 1000° C.
- Fig. 35. Lencauchez Brass Furnace, Fired with Mixed Gas, with Simple Recuperation of the Parallel Counter-Current System.
- Fig. 36. Morgan Gravity-Discharge Billet-Heating Furnace.
- Fig. 37. Morgan Suspended-Roof Billet-Heating Furnace.
- Fig. 38. Siemens Glass Tank Furnace.
- Fig. 39. 50-Ton Campbell Basic Furnace, Steelton, Pa.
- Fig. 40. Kloeene Retort Furnace.
- Fig. 41. Queneau System of Triple Recuperation of the Primary Air, Secondary Air and Gas.
- Fig. 42. Curves Showing, at Different Temperatures, the Theoretical Economies Accruing from the Pre-heating of the Primary Air, Secondary Air and Gas.
- Fig. 43. E. M. F. Curves of Different Thermo-Couples.
- Fig. 44. Pyrometer Cane for the Protection of the Wires of Le Chatelier Thermo-Electric Pyrometer.

- Fig. 45. Apparatus for the Protection of the Thermo-Couple in Roasting Kilns.
- Fig. 46. Apparatus for the Determination of Boiling Points.
- Fig. 47. Apparatus for the Determination of the Boiling Point of Zinc.
- Fig. 48. Fletcher Furnace.
- Fig. 49. Simple Apparatus for the Determination of the Melting and Freezing Points of Metals.
- Fig. 50. Queneau Electric Resistance Crucible Furnace.
- Fig. 51. Electric Resistance Tube Furnace.
- Fig. 52. Siemens-Halske Direct-Reading Galvanometer for Le Chatelier Thermo-Electric Pyrometer.
- Fig. 53. Pellin Registering Galvanometer for Le Chatelier Thermo-Electric Pyrometer.
- Fig. 54. Siemens-Halske Recording Galvanometer for Le Chatelier Thermo-Electric Pyrometer.
- Fig. 55. Optical Pyrometer of Le Chatelier.
- Fig. 56. Féry Heat-Radiation Pyrometer.
- Fig. 57. Féry Heat-Radiation Pyrometer. Lens Type.
- Fig. 58. Féry Heat-Radiation Pyrometer. Mirror Type.
- Fig. 59. Focusing Device of the Féry Heat-Radiation Pyrometer. Mirror Type.
- Fig. 60. Cambridge Scientific Instrument Company Direct-Reading Galvanometer, for the Féry Heat-Radiation Pyrometer.
- Fig. 61. Apparatus for the Determination of the Water Vapor Contained in Furnace Gases.
- Fig. 62. Elliott Gas Apparatus.
- Fig. 63. Showing the Various Positions of 3-way Cock F.
- Fig. 64. Showing the Various Positions of 3-way Cock G.
- Fig. 65. Showing the Various Positions of 3-way Cock H.
- Fig. 66. Elliott Gas Apparatus with Dreshschmidt Platinum Tube for the Determination of Methane and Hydrogen.
- Fig. 67. Section of the "Ados" Automatic Gas Analyzer.
- Fig. 68. Card of the Ados Automatic Gas Analyzer.
- Fig. 69. Cross-Section Through the Mahler Calorimeter (Atwater Modification).

- Fig. 70. Berthelot-Mahler Apparatus Ready for Operation, in the Metallurgical Laboratory of Columbia University.
- Fig. 71. Various Parts of the Berthelot-Mahler Calorimeter.
- Fig. 72. Parr Calorimeter.
- Fig. 73. Junker Gas Calorimeter.
- Fig. 74. Train of Apparatus for the Elementary Analysis of Fuels.
- Fig. 75. Incorrect Flue Connection for a Horizontal Regenerative Chamber.
- Fig. 76. Incorrect Flue Connection for a Vertical Regenerative Furnace.
- Fig. 77. Correct Flue Connection for a Horizontal Regenerative Chamber.
- Fig. 78. Section through a Perforated Block for Recuperative Chamber.
- Fig. 79. Section through the Equivalent Cylindrical Tube.
- Fig. 80. Perforated Firebrick Blocks for the Parallel Counter-Current System of Heat Recuperation.
- Fig. 81. Wailes Water-Sealed Valve.
- Fig. 82. Reversing Valves.
- Fig. 83. Forter Water-Sealed Valve.
- Fig. 84. Regenerative Chambers of a By-Product Coke Oven.
- Fig. 85. Various Types of Ports.
- Fig. 86. Wellman Tilting Furnace.
- Fig. 87. Diagram giving the Thermal Capacities of Gases per Molecular Volumes for any Temperature between  $0^{\circ}$  and  $3000^{\circ}$  C.
- Fig. 88. Diagram giving the Thermal Capacities of Gases per Kilogram for any Temperature between  $0^{\circ}$  and  $3000^{\circ}$  C.



## LIST OF TABLES.

---

1. Table of Thermo-Chemical Reactions.
2. Table of the Volumes and Weights of the Air Required for the Combustion of One Kilogram of Chemically Pure Fuels and of the Volumes and Weights of the Resulting Products of Combustion.
3. Thermal Capacities of Gases, in Absolute Temperatures, per Molecular Volumes.
4. Thermal Capacities of Gases, in Degrees Centigrade, per Molecular Volumes.
5. Thermal Capacities of Gases per Kilogram.
6. Thermal Capacities of Gases, per Molecular Volumes, for Each 200° C.
7. Thermal Capacities of Gases for Each 200° C. per Kilogram.
8. Dissociation of Carbon Dioxide.
9. Dissociation of Carbon Monoxide.
10. Analyses of Various Industrial Gases.
11. Comparative Table of All Systems of Furnaces at Ruling Temperatures of 1000° and 1500°.
12. Table of Goutal Factors.
13. Composition in Weight of the Atmospheric Air.
14. Composition in Volumes of the Atmospheric Air.
15. Weights and Specific Gravities of Gases Found in Furnaces.
16. Specific Heats of Gases per Molecular Volumes.
17. Specific Heats of Gases per Kilogram.
18. Mean Specific Heats Between  $t_2^\circ$  and  $t_1^\circ$  per Kilogram.
19. Values of Factors  $\alpha t$  and  $(1 + \alpha t)$  for Temperatures Between 0° and 1800° C.
20. International Atomic Weights for 1905, of the More Usual Chemical Elements.
21. Conversion Tables.
22. Elementary Analyses and Calorific Powers of Fuels.
23. Prechtl Table of Stack Measurements for Regenerative Furnaces.
24. Coefficients of Heat Conductivity in Calories.

# CONTENTS.

## PART I.

### CHAPTER I.

	PAGE
Heat of combustion and calorific power—Tables 1, 2	
—Thermal capacities and specific heats of gases—	
Tables 3 to 7—Temperatures of combustion of various	
substances under given conditions—Dissociation—	
Tables 8, 9.....	7—36

### CHAPTER II.

Origin and rapid development of gas furnaces—Descrip-	
tion and functions of the essential organs of gas	
furnaces—Modifications and improvements in gas	
furnaces—Table 10 .....	37—52

### CHAPTER III.

Influence of the temperature on the heat utilization in a	
furnace—Definitions: Heat utilized, heat lost, effi-	
ciency, equation of the utilization of heat—Funda-	
mental principles of the utilization of heat in furnaces	
—Hypotheses required for the mathematical theory	
of combustion in the recuperative gas-fired furnaces;	
selection of the method used for the calculation of	
the efficiency .....	53—70

### CHAPTER IV.

Characteristics of direct-fired furnaces and their principal	
industrial applications—Heat lost for all temperatures	
—Furnaces followed by steam boilers—Heat lost in	
them when combustion is effected by the use of a	
large excess of air. ....	71—85

# CONTENTS.

IX

## CHAPTER V.

	PAGE
First group of gas-fired furnaces—Siemens gas-recuperative furnaces, fired with Siemens gas—Details of cases of recuperation numbered one, two, three, four .....	86—96

## CHAPTER VI.

Second group of gas-fired furnaces—Reactions of combustion—Details of cases of recuperation numbered one, two, three, four .....	97—115
--	--------

## CHAPTER VII.

Furnaces making use of the so-called regeneration of the products of combustion—New Siemens furnace—Use of pure carbon dioxide in gas-producers—Details of case—Injection of hot products of combustion in the gas-producer .....	116—121
---	---------

## CHAPTER VIII.

Classification of the various types of furnaces—Table 11. .	122—128
---	---------

## CHAPTER IX.

Experimental study of the heat utilization in furnaces— Methods and data—Ultimate analysis and calorific power of the coal—Measure of the temperatures— Calculation of the efficiency of the furnace .....	129—139
--	---------

## CHAPTER X.

Discussion of the theory of heat recuperation in the light of experimental data—General conclusions and classifications .....	140—144
---	---------

PART II.

CHAPTER XI.

	PAGE
Pyrometric practice and instruments—Forms of couples—Standardization—Crucible method—Electric furnaces—Wire method—Pyrometric galvanometers—Forms of pyrometers.....	147—173

CHAPTER XII.

Gas analysis—Sampling—Sampling tubes—Water-vapor determination—Tests—Manipulation—Calculations—Automatic self-registering gas-analyzing machine.....	174—191
--	---------

CHAPTER XIII.

Calorimetry—Types of calorimeters—Method of using apparatus—Observations required—Calculation of results—Accuracy of calorimetric method—Approximate determination of the calorific power of a fuel by Mahler and Goutal formulas—Table 12.....	192—222
---	---------

CHAPTER XIV.

Elementary fuel analysis—Determination of elements....	223—227
--	---------

PART III.

CHAPTER XV.

Chimneys—Consideration and details of construction—Height—Gas analysis.....	231—237
---	---------

CHAPTER XVI.

Regenerators—Velocities and sojourn of gas currents in regenerative furnaces—Details.....	238—251
---	---------

CONTENTS.

XI

CHAPTER XVII.

	PAGE
Recuperators—Details.....	252—261

CHAPTER XVIII.

Reversing Valves—Hearth—Ports.....	262—271
------------------------------------	---------

CHAPTER XIX.

Powdered fuel—Coal-dust stokers—Details.....	272—282
--	---------

CHAPTER XX.

List of United States patents covering the stoking of powdered fuel.....	283—286
---	---------

CHAPTER XXI.

Tables 13 to 21—Conversion tables—Tables 22 to 24....	287—299
---	---------

BIBLIOGRAPHY.

Fuels and calorimetry—Combustion—Gas analysis—Ther- mal chemistry—Chimneys—Pyrometry—Furnaces— Metallurgy.....	300—305
--	---------

## TRANSLATOR'S NOTE.

---

The knowledge of the lack of any book in English covering the field of a modern study of furnaces led to the preparation of this work. The first part of the volume is a translation of Emilio Damour's "*Le Chauffage Industriel et les Fours à Gas.*" I have supplemented the work with diagrams, plates, tables and numerical problems. The second part of the book has been written to cover the field of Pyrometry, Gas Analysis, Calorimetry, and Fuel Analysis, which have only been touched upon in the work of Damour. Chapters have also been added to give typical examples of the methods to be followed in designing the various parts of gas-recuperative furnaces.

It has been my aim to present a book which would be helpful alike to the works manager and to the theoretician. I have had the opportunity of applying the methods given in tests made upon the furnaces of the New Jersey Zinc Company.

I wish to express my warmest thanks to Myrick N. Bolles, Ph. D., for his contribution of the chapters on "Calorimetry" and the "Ultimate Analysis of Fuels," as well as for his many valuable suggestions in reviewing the manuscript.

A. L. QUENEAU.

South Bethlehem, Pa., September 21, 1905.

## PREFACE.

---

Mr. Queneau has here laid the industrial world, and especially the metallurgical world, under great obligation, by bringing together his own admirable translation of Damour's admirable work and welcome chapters by himself and Dr. Bolles, both of whom I am happy to count among my past students, on the control and efficiency of heating operations through pyrometry and chemical analysis, and on the design of chimneys and of regenerative gas furnaces. To the practicing metallurgist as well as to the advanced student, this work should be very valuable, giving as it does, with well combined clearness and condensation, the results of scientific experiment and of practical experience, and the explanations needed for a firm grasp of the subject. The writers are to be congratulated on having reduced within moderate limits the use of mathematics, probably recognizing, as so many experienced teachers do, that to the minds of nearly all men ideas are brought by far most easily by means of their own native and every-day language, and of visible pictures. If we are to teach, let us teach not only with all our force, but with all our skill, along the line of least resistance to the introduction of new thought, that with the strength and time allotted us we may work the greatest aid to our fellows. To all but a very small group of men mathematical formulæ remain not only a foreign but a repellant language, to be used for giving perfect precision and definition to ideas already expressed in the vernacular, or in extremities when verbal language fails, somewhat as when in despair we turn to Latin or Greek to drive a thought home deeper and surer than we can with English, sometimes perhaps because of its defects, but oftener because of our own clumsiness in its use; or as when we turn to medicine because diet and temperance fail.

By his translation, in which his skill in a foreign language, our

puzzling English, rouses our applause, Mr. Queneau gives us easier access to Damour's valuable work; but in their original chapters he and Dr. Bolles add the fruits of their own keen study, and of their labors at once faithful, strenuous, and efficient.

Let us, their beneficiaries, wish them the fullest enjoyment of the second greatest of human pleasures, the consciousness of work valuable to our kind, well and faithfully done.

HENRY M. HOWE.

Columbia University in the  
City of New York,  
March 23, 1906.



## INTRODUCTION.

---

The problem of industrial heating is very complex and often more difficult of treatment than questions of a purely scientific nature, since in addition to the attainment of a high temperature, the proper heating of a furnace of large dimensions, and other purely technical questions, comes the economical factor, the touchstone of success.

The problem may be stated as follows: An industrial furnace is an apparatus, applicable to any industry, so designed that it will economically produce a high temperature, uniformly distributed in a hearth of large dimensions.

In the general case there are four conditions to be satisfied, namely: Economy, high temperature, all dimensions and all industries. Sometimes the problem becomes more complicated. Thus, a furnace may be required to give alternately high and low temperatures (re-heating furnaces), or to give simultaneously different temperatures in different parts of the hearth (glass furnaces), or, still further, different temperatures in different compartments (Hoffman furnace for bricks and potteries).

For other adaptations, on the contrary, the problem is simplified; for instance, when a low temperature will suffice, a hot flame is useless and even harmful (steam boilers); again, where there is limited hearth area, necessitated by hand working (puddling furnaces). Even the question of fuel economy, which would appear all important in industrial furnaces, may become secondary when it conflicts with factors of greater importance financially, as the efficiency of the men, etc. The engineer should be able to solve not only the general problem, but further to modify his design to suit special cases.

The selection of the proper type of furnace is made difficult by the considerable number of apparatus extant of widely different

designs, all ingenious, the advantages of which are often more apparent than real.

The four general conditions covering the heating problem have often been confused. Siemens' invention of recuperation offered a solution so perfect that it at once realized a saving of from one- to two-thirds of the fuel. Temperatures higher than could be previously obtained permitted the heating of furnaces of dimensions unknown before and, furthermore, the invention was suited to most varied applications, as the fusion of steel and glass—substances differing as radically as possible, from a thermal point of view.

The rapid advance created by one form of apparatus caused some confusion. Engineers and builders came to think that the different phases of the heating problem were all intimately connected. High temperature and recuperation appeared to be functions of each other, and gas firing, with recuperation, seemed to be suited only to large units and ill adapted to small ones; even the character of the substances to be heated was lost sight of.

These ideas are not only most inaccurate, but also detrimental to the correct study of furnaces. To be convinced of this, it is sufficient to recall that, disregarding economy, it is possible to obtain very high temperatures without recuperation by an independent heating of the air of combustion, as was done for many years in blast-furnace practice; likewise, in ceramics, it was possible to heat very large kilns without recourse to gas firing; there are instances even in which fuel economy is not to be sought at all by recuperation. We will show this to be the case for low temperatures.

In order to be able to solve rationally the many problems met with in industrial heating, the various phases of heat utilization must be taken up, and the several questions which have been united in the happy solution offered in the gas-fired recuperative furnaces must be separated.

A complete study of the art of heating comprises, then, the following chapters:

1. Heat utilization in furnaces; fuel economy; recuperation of lost heat.

2. Production of high temperatures; influence of pre-heating the gases; radiation losses.

3. Furnace dimensions; large furnaces with long flames; small furnaces with short flames; influence of the velocity of the gases and of the shape of the issuing ports.

4. Applications of gas-fired furnaces to varied industries—metallurgy, ceramics, etc.; design of the furnace as influenced by the character of the body to be heated.

5. Finally, fuel gasification calls for special study, to ascertain the most suitable type of producer and the best methods of gasification, which should vary according as the gas is used hot or cold, and whether with or without recuperation.

Of all these questions the one of heat utilization is doubtless the most interesting, now that the production of high temperatures is no longer a serious problem. Economy is the constant aim of modern industry. It is a problem which is and always will be of necessity interesting, and therefore it is the one which will be treated first.

It is the purpose of the present work to study the means of improving the utilization of heat and of decreasing, through recuperation, the loss of heat in the waste products. To accomplish this study, the supposition will be made that the furnaces are governed by the physical laws of combustion and exchange of calories, each phenomenon taking place completely. At first the practical considerations, as that of time, which limit most of these phenomena, will not be taken into account. In a word, a Theory of Recuperation will be built, which will allow the classification of furnaces according to their maximum efficiency. This will constitute the first part of this book.

In the second part will be introduced into the discussion the data given by the experimental study of furnaces. It will then become possible to make a thermic balance sheet which will serve for reference, and also to give the ultimate classification of the various systems of heating in actual use.

This will then fully cover the first problem: Heat Utilization and Recuperation.

EMILIO DAMOUR.



## **PART I**

---

# **INDUSTRIAL FURNACES EXPERIMENTAL DETERMINATION OF THEIR EFFICIENCIES**

**BY**

**EMILIO DAMOUR**

**Ingenieur Civil des Mines**

**Chef des Travaux Chimiques a l'Ecole Nationale Superieure des Mine**

**Authorized Translation and Additions**

**by**

**A. L. J. QUENEAU, B.S. (Paris), E.M., A.M. (Columbia)**

**Consulting Engineer, The New Jersey Zinc Company**





## PART I.

---

### THEORETICAL STUDY OF RECUPERATION.

#### CHAPTER I.

##### SCIENTIFIC DATA NECESSARY FOR THE STUDY OF COMBUSTION PHENOMENA.

The basis for all thermic study is the knowledge of the heats of combustion, for the determination of which science is indebted to Vieille and Berthelot, who used for their work the calorimetric bomb. But these data were insufficient to solve the problem we have undertaken, until Mallard and Le Chatelier had determined the specific heats and thermal capacities of gases.<sup>1</sup> It is easily seen, then, that it is only recently that it has been possible to solve the theoretical question of the industrial production and utilization of heat.

*Heat of Combustion and Calorific Power.*—By heat of combustion under constant pressure, or more simply heat of combustion of a chemical element or of a well defined chemical compound, is meant the number of calories<sup>2</sup> liberated by the combination with oxygen of a number of grams of this substance equal to its molecular weight.<sup>3</sup> By definition, when the body is a gas, the molecular weight corresponds to a volume, alike for all gases, of 22.32 liters. This unity of volume, adopted by Berthelot in his thermochemical work, is what we will call the Molecular Volume.

<sup>1</sup> Mallard and Le Chatelier made these determinations jointly, in connection with their well known work as members of the "Commission du Grisou." This explains without doubt why these data, all important to science and industry, have been promulgated so slowly.

<sup>2</sup> We make use of the large calory throughout this work.

<sup>3</sup> The molecular weights of elements are generally double their atomic weights; the molecular weights of compounds are equal to the sum of the molecular weights of the constituent elements.

TABLE 1.  
TABLE OF THERMO-CHEMICAL REACTIONS

Substance	Molecular Formula	Molecular Weight	Molecular Volume	Reaction of Combustion	Lib. Cal. per Mol. Vol.	Remarks	Heat of Formation per Mol. Vol.	Available Calories per Kilogram of Substance	Oxygen Required of Air	Weight of Products of Combustion
Hydrogen.....	H <sub>2</sub>	Gr. 2	Lit. 22.32	H <sub>2</sub> + $\frac{1}{2}$ O <sub>2</sub> = H <sub>2</sub> O.....	69.0	Water as Liquid.	.....	34500	8.000	Kcal. 9.000
Carbon.....	C	12	22.32	C + $\frac{1}{2}$ O <sub>2</sub> = CO.....	58.2	Water as Vapor.	.....	29100	1.333	2.333
Carbon Monoxide.....	CO	28	22.32	CO + $\frac{1}{2}$ O <sub>2</sub> = CO <sub>2</sub> .....	29.4	.....	.....	2602	5.777	2.333
Carbon.....	C	12	22.32	C + O <sub>2</sub> = CO <sub>2</sub> .....	68.2	.....	29.4	2436	2.472	1.571
Carbon.....	C	12	22.32	C + O <sub>2</sub> = CO <sub>2</sub> .....	97.6	.....	.....	8080	2.667	3.667
Methane.....	CH <sub>4</sub>	16	22.32	CH <sub>4</sub> + 2O <sub>2</sub> = CO <sub>2</sub> + 2H <sub>2</sub> O.....	195.2	Water as Vapor.	18.8	12200	4.000	CO <sub>2</sub> = 2.750
Acetylene.....	C <sub>2</sub> H <sub>2</sub>	26	22.32	C <sub>2</sub> H <sub>2</sub> + 2 $\frac{1}{2}$ O <sub>2</sub> = 2CO <sub>2</sub> + H <sub>2</sub> O.....	213.5	Water as Liquid.	.....	13063	3.076	H <sub>2</sub> O = 2.250
Acetylene.....	C <sub>2</sub> H <sub>2</sub>	26	22.32	C <sub>2</sub> H <sub>2</sub> + 2 $\frac{1}{2}$ O <sub>2</sub> = 2CO <sub>2</sub> + H <sub>2</sub> O.....	304.9	Water as Vapor..	-51.5	11727	3.076	CO <sub>2</sub> = 3.355
Ethane.....	C <sub>2</sub> H <sub>6</sub>	30	22.32	C <sub>2</sub> H <sub>6</sub> + 3 $\frac{1}{2}$ O <sub>2</sub> = 2CO <sub>2</sub> + 3H <sub>2</sub> O.....	315.7	Water as Liquid.	29.9	12142	3.733	H <sub>2</sub> O = .691
Ethane.....	C <sub>2</sub> H <sub>6</sub>	30	22.32	C <sub>2</sub> H <sub>6</sub> + 3 $\frac{1}{2}$ O <sub>2</sub> = 2CO <sub>2</sub> + 3H <sub>2</sub> O.....	339.9	Water as Vapor.	.....	11330	3.733	CO <sub>2</sub> = 2.833
Ethylene.....	C <sub>2</sub> H <sub>4</sub>	28	22.32	C <sub>2</sub> H <sub>4</sub> + 3O <sub>2</sub> = 2CO <sub>2</sub> + 2H <sub>2</sub> O.....	372.3	Water as Liquid.	.....	12410	3.429	H <sub>2</sub> O = 1.800
Ethylene.....	C <sub>2</sub> H <sub>4</sub>	28	22.32	C <sub>2</sub> H <sub>4</sub> + 3O <sub>2</sub> = 2CO <sub>2</sub> + 2H <sub>2</sub> O.....	319.6	Water as Vapor.	-8.0	11414	3.429	CO <sub>2</sub> = 3.143
Sulphur.....	S	32	.....	S + O <sub>2</sub> = SO <sub>2</sub> .....	241.2	Water as Liquid.	.....	11858	1.000	H <sub>2</sub> O = 1.286
Sulphur.....	S	32	.....	S + O <sub>2</sub> = SO <sub>2</sub> .....	69.2	As Gas.....	.....	2170	1.000	2.000
Sulphur.....	S	32	.....	S + O <sub>2</sub> = SO <sub>2</sub> .....	76.8	In Solution.....	.....	2400	1.500	2.500
Sulphur.....	S	32	.....	S + O <sub>2</sub> = SO <sub>2</sub> .....	103.6	As Solid.....	.....	3230	1.500	2.500
Sulphur.....	S	32	.....	S + O <sub>2</sub> = SO <sub>2</sub> .....	141.0	In Solution.....	.....	4400	1.500	2.500
Sulphur.....	S	32	.....	S + O <sub>2</sub> = SO <sub>2</sub> .....	91.8	As Gas.....	.....	2800	1.500	2.500



TABLE 2.  
THE VOLUMES AND WEIGHTS OF THE AIR REQUIRED FOR THE COMBUSTION OF ONE KILOGRAM OF CHEMICALLY PURE FUELS AND OF THE VOLUMES AND WEIGHTS OF THE RESULTING PRODUCTS OF COMBUSTION.

One Kilogram of	Burning to	Requires				AND PRODUCTS AS COMBUSTION PRODUCTS						
		in Kilograms			in Cubic Meters		Cubic Meters					
		Oxy- gen	Nitro- gen	Air	Oxy- gen	Nitro- gen	Air	CO	CO <sub>2</sub>	H <sub>2</sub> O	N	Total
C.....	CO	1.33	4.46	5.79	0.93	3.55	4.48	2.33 1.86	.....	.....	4.46 3.55	6.79 5.41
CO.....	CO <sub>2</sub>	0.57	1.91	2.48	0.39	1.53	1.92	.....	1.57 0.80	.....	1.91 1.52	3.48 2.32
C.....	CO <sub>2</sub>	2.67	8.93	11.60	1.87	7.15	9.02	.....	3.67 1.87	.....	8.93 7.12	12.90 8.99
H <sub>2</sub> .....	H <sub>2</sub> O	8.00	26.72	34.72	5.59	21.29	26.88	.....	.....	9.00 11.19	26.72 21.29	35.72 32.48
CH <sub>4</sub> .....	CO <sub>2</sub> + 2H <sub>2</sub> O	4.00	13.36	17.36	2.80	10.64	13.44	.....	2.75 1.40	2.25 2.79	13.36 10.65	18.36 14.84
C <sub>2</sub> H <sub>4</sub> .....	2CO <sub>2</sub> + 2H <sub>2</sub> O	3.43	11.49	14.92	2.40	9.12	11.52	.....	3.14 1.60	1.29 1.60	11.49 9.12	15.92 12.32
C <sub>2</sub> H <sub>6</sub> .....	2CO <sub>2</sub> + 3H <sub>2</sub> O	3.73	12.42	16.15	2.07	9.90	11.97	SO <sub>2</sub>	2.93 1.49	1.80 2.23	12.42 9.90	17.15 13.62
S.....	SO <sub>2</sub>	1.00	3.33	4.33	.69	2.65	3.34	2.00 0.70	.....	.....	3.33 2.65	5.33 3.36

Friedrich Toldt, "Regenerativ Gas-ofen," page 50.

When the body under combustion is a fuel, coal, coke, etc., at the ordinary temperature, the heat of combustion is designated more specifically by the name of Calorific Power. This experimental constant, easily determined by means of the Mahler bomb, represents, then, the available calorific energy—that is, the quantity of heat the complete utilization of which is to be sought, since all industrial combustions take place without compression, at a pressure very nearly equal to that of the atmosphere. These two data—the heat of combustion and the calorific power under constant pressure—are those that perform the fundamental function in the theoretical and practical questions occurring in industrial heating.

The heat of combustion of chemical elements, as well as the heats of combustion produced by the combination of these elements, have been determined by Berthelot and are published in the “*Annuaire du Bureau des Longitudes*.” From the 1897 edition we have taken the figures required for our study, and have formed from them a table which will be sufficient for all problems of combustion in furnaces.

*Thermal Capacities and Specific Heats of Gases.*—When a gas maintained at a constant pressure is brought from an initial temperature  $T_0$  to a higher temperature  $T_1$ , the number of calories absorbed by the gas in this operation is called the Thermal Capacity between the temperatures  $T_0$  and  $T_1$ .

Inversely, the Thermal Capacities will give the number of calories set free by the gas when cooling from  $T_1$  to  $T_0$ . These constants are the basis for all calculations of exchange, in calories, in the phenomena of heating and combustion.

The Specific Heat of a gas at any temperature, which we do not need to limit, is easily derived from its Thermal Capacity. It is the first derivative of the function expressing the Thermal Capacity. It is not possible, inversely, to derive from the specific heat of a gas at a given temperature, or even from the mean specific heat between the temperatures  $0^\circ$  and  $100^\circ \text{C.}$ , the Thermal Capacity of the gas at a temperature above  $100^\circ \text{C.}$

The fact is that all Specific Heats are variable and increase in general with the temperature. If the law of increase is unknown

it is evidently impossible to go from the derivative to the primitive function, that is, from the Specific Heat to the Thermal Capacity.

It follows that the Specific Heats of gases under constant pressure between 0° and 100° C., determined by Regnault, are not sufficient to calculate the quantity of heat absorbed by a gas in heating or radiated in cooling, and hence all calculations based on these figures are subject to a more or less grave error, the importance of which could not formerly be estimated.<sup>1</sup> In short, the problem of combustion and exchange of calories cannot be taken up with the single datum of the specific heats between 0° and 100° C.

The formulas expressing the law of heating of gases under constant pressure have been given by Mallard and Le Chatelier as a function of absolute temperature.

The Thermal Capacities of Gases from absolute 0° (−273° C.) to a temperature  $T = 273° + t$  may be expressed by a parabolic formula of two parameters:

$$Q = a \frac{T}{1000} + b \frac{T^2}{1000^2}$$

in which "a" is a constant, common to all gases, equal to 6.5, and "b" is another constant, variable for the different gases; its values are:

Perfect Gases	Water Vapor	Carbon Dioxide	Methane
O <sub>2</sub> , N <sub>2</sub> , H <sub>2</sub> , CO	H <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>
0.6	2.9	3.7	6.0

It follows that the total Thermal Capacities of a Molecular Volume (22.32 liters) of any gas between

$$t_0 = T_0 - 273° \text{ and } t = T - 273°$$

will be expressed by the formulas given in Table 3.

<sup>1</sup> A large number of calculations of heat balance-sheets have been published, based on these insufficient data.

TABLE 3.

THEMAL CAPACITIES OF GASES PER MOLECULAR VOLUMES  
IN ABSOLUTE TEMPERATURES

Gas	Under Constant Pressure	Under Constant Volume
Perfect Gases ( $O_2, N_2, H_2, CO$ )	$6.5 \frac{T-T_0}{10^3} + .6 \frac{T^2-T_0^2}{10^6}$	$4.5 \frac{T-T_0}{10^3} + .6 \frac{T^2-T_0^2}{10^6}$
Water Vapor, $H_2O$ .....	$6.5 \frac{T-T_0}{10^3} + 2.9 \frac{T^2-T_0^2}{10^6}$	$4.5 \frac{T-T_0}{10^3} + 2.9 \frac{T^2-T_0^2}{10^6}$
Carbon Dioxide, $CO_2$ .....	$6.5 \frac{T-T_0}{10^3} + 3.7 \frac{T^2-T_0^2}{10^6}$	$4.5 \frac{T-T_0}{10^3} + 3.7 \frac{T^2-T_0^2}{10^6}$
Methane, $CH_4$ .....	$6.5 \frac{T-T_0}{10^3} + 6.0 \frac{T^2-T_0^2}{10^6}$	$4.5 \frac{T-T_0}{10^3} + 6.0 \frac{T^2-T_0^2}{10^6}$

TABLE 4.

THEMAL CAPACITIES OF GASES PER MOLECULAR VOLUMES  
IN CENTIGRADE DEGREES

Gases	Under Constant Pressure	Under Constant Volume
Perfect Gases ( $O_2, N_2, H_2, CO$ )	$6.83 \frac{t}{10^3} + .6 \frac{t^2}{10^6}$	$4.83 \frac{t}{10^3} + .6 \frac{t^2}{10^6}$
Water Vapor, $H_2O$ .....	$8.08 \frac{t}{10^3} + 2.9 \frac{t^2}{10^6}$	$6.08 \frac{t}{10^3} + 2.9 \frac{t^2}{10^6}$
Carbon Dioxide, $CO_2$ .....	$8.52 \frac{t}{10^3} + 3.7 \frac{t^2}{10^6}$	$6.52 \frac{t}{10^3} + 3.7 \frac{t^2}{10^6}$
Methane, $CH_4$ .....	$9.78 \frac{t}{10^3} + 6.0 \frac{t^2}{10^6}$	$7.78 \frac{t}{10^3} + 6.0 \frac{t^2}{10^6}$

TABLE 5.

THEMAL CAPACITIES OF GASES PER KILOGRAM IN CENTIGRADE DEGREES

Gases	Under Constant Pressure	Under Constant Volume
Oxygen.....	$.213t + 19 \times 10^{-6}t^2$	$.150t + 19 \times 10^{-6}t^2$
Nitrogen and Carbon Monoxide....	$.243t + 21 \times 10^{-6}t^2$	$.171t + 21 \times 10^{-6}t^2$
Hydrogen.....	$.3400t + 300 \times 10^{-6}t^2$	$.240t + 300 \times 10^{-6}t^2$
Water Vapor.....	$.447t + 162 \times 10^{-6}t^2$	$.335t + 162 \times 10^{-6}t^2$
Carbon Dioxide.....	$.193t + 84 \times 10^{-6}t^2$	$.15t + 84 \times 10^{-6}t^2$
Methane.....	$.608t + 374 \times 10^{-6}t^2$	$.491t + 374 \times 10^{-6}t^2$

TABLE 6.

THERMAL CAPACITIES OF GASES PER MOLECULAR VOLUME

Temperatures	O <sub>2</sub> , N <sub>2</sub> , H <sub>2</sub> , CO	H <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	$\delta = .002t$
0 C.	0	0	0	0	0
200.....	1.39	1.73	1.85	2.19	0.4
400.....	2.82	3.69	3.99	4.85	0.8
600.....	4.31	5.87	6.44	8.02	1.2
800.....	5.82	8.23	9.18	11.46	1.6
1000.....	7.43	10.98	12.22	15.77	2.0
1200.....	9.05	13.87	15.55	20.37	2.4
1400.....	10.73	17.00	19.18	25.44	2.8
1600.....	12.46	20.35	23.10	30.99	3.2
1800.....	14.21	23.88	27.21	36.86	3.6
2000.....	16.05	27.76	31.84	43.55	4.0
2200.....	17.91	31.82	36.65	50.54	4.4
2400.....	19.84	36.10	41.76	58.02	4.8
2600.....	21.81	40.62	47.16	66.04	5.2
2800.....	23.82	45.64	52.84	74.42	5.6
3000.....	25.89	50.64	58.86	83.34	6.0

TABLE 7.

THERMAL CAPACITIES OF GASES PER KILOGRAM.

Temperatures	O <sub>2</sub>	N <sub>2</sub> , CO	H <sub>2</sub>	H <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	$\delta = .09t$
0 C.	0	0	0	0	0	0	0
200.....	47.3	50	700	100	43.1	136.6	18
400.....	88.0	100	1400	203	91.0	303.0	36
600.....	134.0	154	2150	328	145.0	499.0	54
800.....	181.0	207	2900	461	208.0	728.0	72
1000.....	232.0	264	3700	609	277.0	982.0	90
1200.....	284.0	325	4650	770	354.0	1269.0	108
1400.....	334.0	383	5350	943	435.0	1584.0	126
1600.....	391.0	445	6250	1130	523.0	1931.0	144
1800.....	444.0	508	7100	1330	618.0	2307.0	162
2000.....	503.0	575	8050	1542	728.0	2712.0	180
2200.....	558.0	637	8950	1751	840.0	3148.0	198
2400.....	620.0	708	9900	1985	950.0	3614.0	216
2600.....	681.0	777	10900	2241	1070.0	4109.0	234
2800.....	735.0	850	11900	2520	1200.0	4635.0	252
3000.....	810.0	921	12950	2799	1355.0	5190.0	270

These formulas make it possible to find the Thermal Capacities between any two temperatures.

The Specific Heats at any temperatures are to be obtained by taking the first derivative of the formulas for the Thermal Capacities. They are given in Table 2. This, however, is without interest to our study. As we will constantly be obliged to compute the Thermal Capacities, it has appeared advisable to reproduce

them in a table, for each 200°, between the limits of temperature found in industrial furnaces.

By plotting the expression for Thermal Capacity in rectangular coördinates, we obtain a curve from which it is possible to find, with sufficient accuracy, the values of the Thermal Capacity for any temperature.

*Temperatures of Combustion.*—The knowledge of the Heats of Combustion and of the Thermal Capacities makes it possible to solve a fundamental problem in our study—the problem of the Temperatures of Combustion.

By “temperature of combustion” is meant the temperature to which the gaseous products are brought, after combustion under constant pressure. It is supposed that this action takes place so rapidly that radiation is negligible and that the enclosure is atherman. These conditions are nearly similar to those met in practice; the pressure in the furnace is that of the atmosphere. The instantaneousness of action and the athermancy of the furnace are not entirely fulfilled; this explains why the temperature of a flame in a furnace is inferior to the temperature of combustion. However, other things being equal, the temperatures of combustion allow an estimate of the practical value of a fuel which the calorific power and the specific heats alone cannot do. Formerly many computations, based only on the calorific power of the gases, were made in order to estimate the value of a special furnace; these data are always insufficient.

The computation of the exact temperature of combustion is logically derived from the knowledge of the Thermal Capacity. Soon after the completion of the work of the Commission du Grisou, Professor Le Chatelier showed how the former theoretical computations of temperatures were inaccurate.

*General Equation of the Temperature of Combustion.*—During combustion the heat liberated, under constant pressure, is used only to raise the temperature of the final gaseous mixture; and since by hypothesis the phenomenon is atherman, there is equality between the latent heat of combustion and the sensible heat contained in the gaseous mixture after combustion has taken place, hence the equation:

$$\Sigma L = \Sigma a (T - T_0) + \Sigma b (T^2 - T_0^2) \quad (1)$$

This is a corollary of Joule's principle. Since no work is done under constant pressure, the sum of the quantities of heat in play in a closed cycle is equal to zero.

$$L = \int_0^t c dt \quad (2)$$

The equation (1) is of the second degree, and gives the value of  $T$  as a function of  $T_0$ . The solution of the equation may be tedious in case of a complex mixture of gases. It is much quicker to use the graphic method, if a table of Thermal Capacities is at hand.

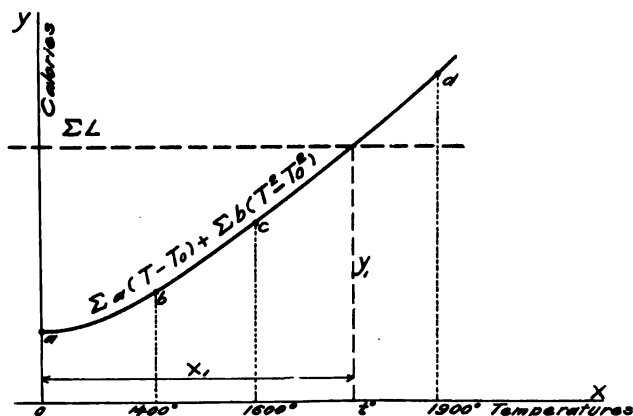


FIG. 1.—GRAPHIC METHOD FOR THE DETERMINATION OF THE TEMPERATURES OF COMBUSTION.

*Graphic Method for the Computation of the Temperatures of Combustion.*—The intersection of the line  $\Sigma L$  with the parabola

$$\Sigma a (T - T_0) + \Sigma b (T^2 - T_0^2)$$

is to be found. The parabola is traced by points corresponding to temperatures for which the Thermal Capacities are given in the table (see preceding paragraphs), and thus the solution of the equa-

tion is obtained at once. The graphic method is used entirely in these pages; it cannot be commended too highly for rapid computations; it has the further advantage that, though not so accurate as the mathematical method, it is much less liable to error.

Unless otherwise stated, all the computations given in the present work are made with the supposition that a molecular weight of the fuel is burned. This molecular weight will be taken as the basic unit. It is evident that, were any other weight taken, the same temperature would be obtained, because in the general equation the masses do not enter as a factor.

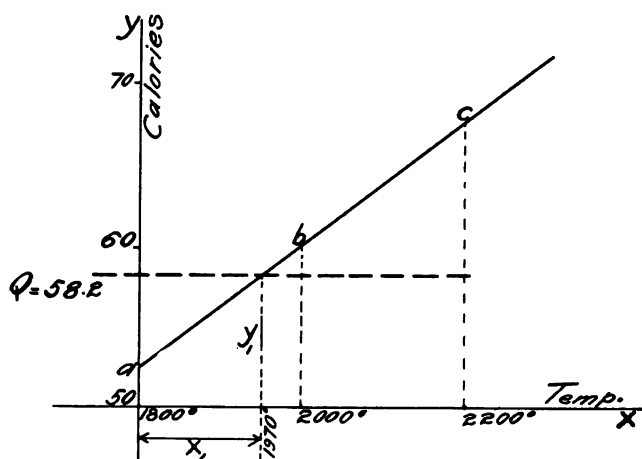


FIG. 2.—TEMPERATURE OF COMBUSTION OF HYDROGEN IN AIR.

*Temperature of Combustion of Hydrogen in Cold Air.*—In order to burn the molecular weight of hydrogen, 2 grams (22.32 liters), to water vapor, a half molecular volume of oxygen ( $\frac{1}{2}\text{O}_2$ ) is required; this oxygen will be accompanied by about a quadruple volume of nitrogen<sup>1</sup> ( $2\text{N}_2$ ), that is to say, two molecular volumes. From the table of Thermal Capacities may be found the number of

<sup>1</sup> In volume air is composed of 20.8 parts of oxygen, and of 79.2 parts of nitrogen, or of one part of oxygen for 3.8 parts of nitrogen, or about 4 parts. To simplify our computations we will always take the ratio 1 : 4. For more accurate ratios see Tables 13 and 14.



calories required to raise this gaseous mixture to different temperatures.

Products of Combustion	1800°	2000°	2200°
	<sup>a</sup>	<sup>b</sup>	<sup>c</sup>
H <sub>2</sub> O.....	23.86	27.76	31.82
2 N <sub>2</sub> .....	28.42	32.10	35.82
Total.....	52.28	59.86	67.64

The total heat liberated by 2 grams of hydrogen burning to water vapor is 58.2 calories, which is the value of  $\Sigma L$  in the general equation. From the above table it is seen at a glance that the unknown temperature of combustion is included between 1800° and 2000° C. If the curve characterized by the three points *a*, *b*, *c* is drawn, its intersection with the line  $Q = 58.2$  will give, graphically, the temperature of combustion of hydrogen: 1970° C.

*Temperature of Combustion of Carbon.*—Burned with cold air and without any excess of air, the temperature of combustion of carbon is 2040° C. (see page 21); but if we suppose that the products of combustion carry 5% of free oxygen, or 25% excess of air, the temperature is lowered to 1650°.

These two results are interesting, as showing the maximum temperatures that can be obtained in a furnace. These temperatures represent the limit of temperatures of direct-fired furnaces. In such furnaces it is practically impossible to secure complete combustion without a large excess of air, rarely less than 5%. This temperature of 1650° C., which does not allow for radiation and all other exterior losses of heat, shows conclusively the impossibility of obtaining high temperatures by direct firing.

If there is an excess of 5% of carbon monoxide in the products of combustion, the temperature reaches a higher figure—1930° C. Such a combustion is to be obtained only in gas firing; this indicates that, in order to obtain high temperatures, it is advisable, in gas furnaces, to run with excess of carbon monoxide in the waste products, though evidently it is less economical, the coal consumption being higher. If economy and temperature are both taken into account, each particular case must be taken into considera-

tion, but in general it may be said that, for furnaces requiring high temperatures, the running with excess of carbon monoxide is to be preferred. Excess of air, on the other hand, is preferable for low-temperature furnaces, as steam boilers, where it is of prime importance that the combustion be complete.

In both cases, the running without excess of either air or carbon monoxide is more advantageous in respect to the amount of coal burned.

*General Case.*—Find the temperature of combustion of a producer gas, the volumetric analysis of which is as follows:

Carbon Dioxide.....	5.0%
Carbon Monoxide.....	20.0
Hydrogen.....	12.0
Methane.....	3.0
Water Vapor.....	2.0
Nitrogen.....	58.0
	<hr/> 100.0%

The gas is pre-heated to 1000° C.; the air of combustion is also pre-heated to 1000° C.

The volume of air required for the complete combustion of the gas is obtained as follows:

20 volumes of CO require 10 volumes of oxygen

12	"	H <sub>2</sub>	"	6	"	"
3	"	CH <sub>4</sub>	"	6	"	"

Or, for 100 volumes of the gas, 22 volumes of oxygen are required or 110 volumes of air.

The heat brought by the air and gas at 1000° C. is as follows:

Gas	Composition in Mol. Vol.	Calories as Sensible Heat	Calories as Latent Heat
CO <sub>2</sub>	.05	.6	.....
CO	.20		13.6
H <sub>2</sub>	.12	6.6	6.9
N <sub>2</sub>	.58		
CH <sub>4</sub>	.03	.5	5.6
H <sub>2</sub> O	.02	.2	.....
	<hr/> 1.00		
Air required....	<hr/> 1.10	8.1	
Total.....		16.0	26.1
<hr/> Σ L = 42.1 Calories <hr/>			

The following table gives the Thermal Capacities for the volumes of the products of combustion, for different temperatures.

Products of Combustion	Volumes	Thermal Capacities		
		2000°	2200°	2400°
CO <sub>2</sub> .....	0.28	8.5	10.3	11.7
N <sub>2</sub> .....	1.46	23.4	26.1	28.9
H <sub>2</sub> O.....	.20	5.5	6.3	7.2
		37.4	42.7	47.8

It is seen at a glance that the temperature of combustion is nearly 2200° C. This very high temperature shows the practical value of pre-heating the air and the gas for high temperatures.

*Combustion of Carbon Monoxide in Cold Air.*—The weight of carbon monoxide to be burned is 28 grams, corresponding to the molecular volume, 22.32 liters; the heat liberated is 68.2 calories.

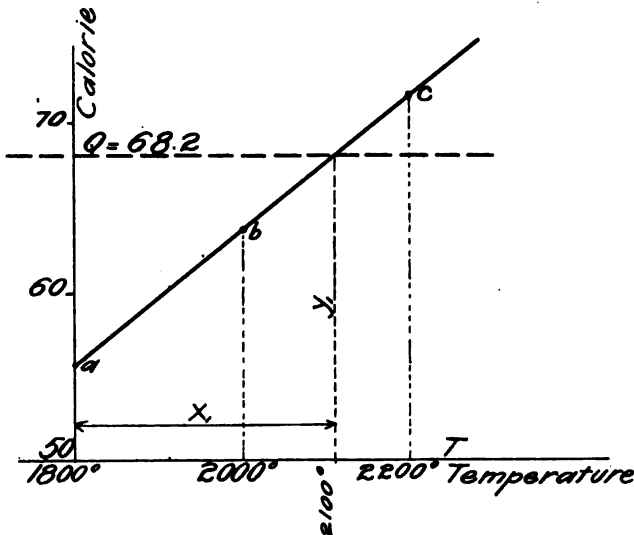


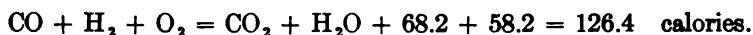
FIG. 3.—TEMPERATURE OF COMBUSTION OF CARBON MONOXIDE IN AIR.

By plotting the curve characterized by the three points *a*, *b*, *c*, and the straight line  $Q = 68.2$ , we find their intersection to correspond to a temperature of  $2100^{\circ}\text{C}$ .

The following table gives the thermal capacities:

Waste Products	Thermal Capacities		
	$1800^{\circ}$	$2000^{\circ}$	$2200^{\circ}$
$\text{CO}_2$ .....	27.2	31.8	36.6
$\text{N}_2$ .....	28.4	32.1	35.8
	$a = 55.6$	$b = 63.9$	$c = 72.4$

*Temperature of Combustion of the Theoretical Water Gas ( $\text{CO} + \text{H}_2$ ) in Cold Air.*—Its combustion takes place according to the following reaction:



Hence the following table and diagram (Fig. 4).

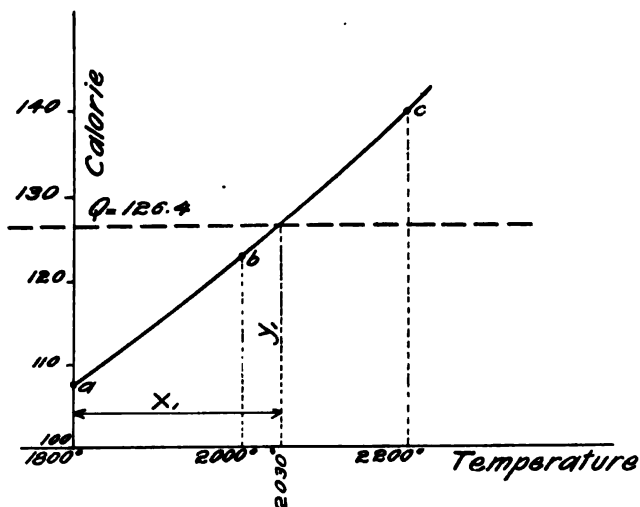


FIG. 4.—TEMPERATURE OF COMBUSTION OF WATER GAS ( $\text{CO} + \text{H}_2$ ) IN AIR

Waste Products	Thermal Capacities		
	1800°	2000°	2200°
CO <sub>2</sub> .....	27.2	31.8	36.6
H <sub>2</sub> O.....	23.8	27.7	31.8
4N <sub>2</sub> .....	56.8	64.2	71.6
Total.....	107.8	123.7	140.0

The intersection of the two lines gives 2030° C. as the temperature of Combustion.

The preceding results show that if carbon monoxide, CO, is free from nitrogen, its temperature of combustion is higher than that of hydrogen; also, that that of the theoretical water gas is intermediate between the two.

*Temperature of Combustion of Carbon in Cold Air.*—The weight of amorphous carbon burned is 12 grams. This corresponds to the molecular volume 22.32 liters of carbon dioxide, CO<sub>2</sub>. Heat liberated, 97.6 calories. The following table and diagram give a temperature of combustion of 2040° C.:

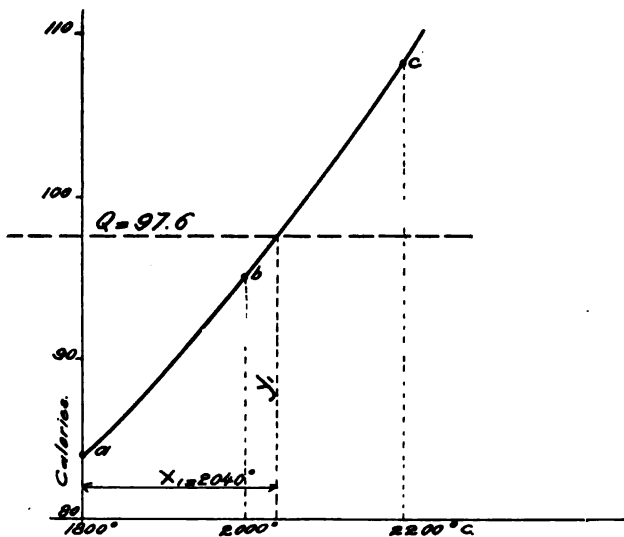


FIG. 5.—TEMPERATURE OF COMBUSTION OF CARBON IN AIR.

Products of Combustion	Thermal Capacities		
	1800°	2000°	2200°
CO <sub>2</sub> .....	27.2	31.8	36.6
4N <sub>2</sub> .....	56.8	64.2	71.6
	84.0	96.0	108.2

X = 2040° C.

*Temperature of Combustion of Bituminous Coal in Cold Air.*—  
Analysis of the bituminous coal:

Total Carbon.....	75.2%
Oxygen O <sub>2</sub> .....	8.2
Nitrogen N <sub>2</sub> .....	1.0
Hydrogen H <sub>2</sub> .....	5.2
Hygroscopic Water H <sub>2</sub> O.....	3.4
Ash.....	7.0
	100.0%

The Calorific Power determined in a Mahler bomb calorimeter was found to be 7423 calories.

The combustion of this coal will yield waste products containing the following:

Carbon Dioxide,  
Water of Combination,  
Hygroscopic Water,  
Nitrogen coming from the coal,  
Nitrogen coming from the air.

The composition of the products of combustion in Molecular Volumes is obtained as follows:

Twelve grams of carbon give, in burning, one molecular volume of carbon dioxide; 75.2 grams give 6.27 vol.

Two grams of hydrogen give, in burning, one molecular volume of water vapor; 5.2 grams give 2.6 in molecular vol.

Eighteen grams of water give one molecular volume of water vapor; 3.4 grams give 0.19 vol., a total of 2.79 vol. of water vapor.

The oxygen required for combustion is:

	6.27 volumes for the formation of CO <sub>2</sub>	
	1.30	H <sub>2</sub> O
Molecular volume corresponding to 8.2 grams of Oxygen in the fuel, 8.2 ÷ 32 = .25		
molecular volumes.		
Oxygen required from the air, 7.57 — .25 = .....	7.320	Vol.
Nitrogen required " 7.32 × 4 = .....	29.280	"
from the coal, 1.0/28 = .....	0.036	"
Total volume of Nitrogen.....	29.32	"

The volumetric composition of the waste products is, then:

Carbon Dioxide.....	6.27
Water Vapor.....	2.79
Nitrogen.....	29.32

The combustion of 100 grams of coal liberated 742.3 calories. Referring to the table of Thermal Capacities per M. V.:

Products of Combustion	Mol. Vol.	Thermal Capacities		
		1600°	1800°	2000°
CO <sub>2</sub> .....	6.27	144.8	170.6	199.6
H <sub>2</sub> O.....	2.79	56.7	66.5	77.4
N <sub>2</sub> .....	29.32	365.3	416.5	471.0
Total.....	.....	566.8	653.6	748.0

It is seen at once that the maximum temperature to be realized with this coal in a direct-fired furnace is nearly 2000° C.

*Temperature of Combustion of Siemens Producer-Gas Burned with Pre-heated Air.*—The composition of the theoretical Siemens producer-gas (no steam being injected under the grate) is CO + 2N<sub>2</sub>.

Both the air and gas are pre-heated to 1000° C. One-half molecule of oxygen is needed for the molecule of carbon monoxide: this oxygen carries with itself two molecules of nitrogen.

Calories liberated by the combustion = .....	68.2
" brought by one vol. of CO.....	7.43
" " " ½ vol. O <sub>2</sub> .....	3.72
" " " ½ vol. of N <sub>2</sub> .....	29.72
Total.....	109.07

The thermal capacities of the combustion products are:

Gas	1800°	2000°	2200°	2400°
CO <sub>2</sub> .....	27.2	31.8	36.6	41.8
4 N <sub>2</sub> .....	56.8	64.2	71.6	79.4
Total.....	84.0	96.0	108.2	121.2

By plotting the curves of *Q* and of the thermal capacities, we find the temperature of combustion to be 2215° C.

In the same manner we find that, if both the air and the gas are pre-heated to 500° C., the temperature of combustion is 1865° C.

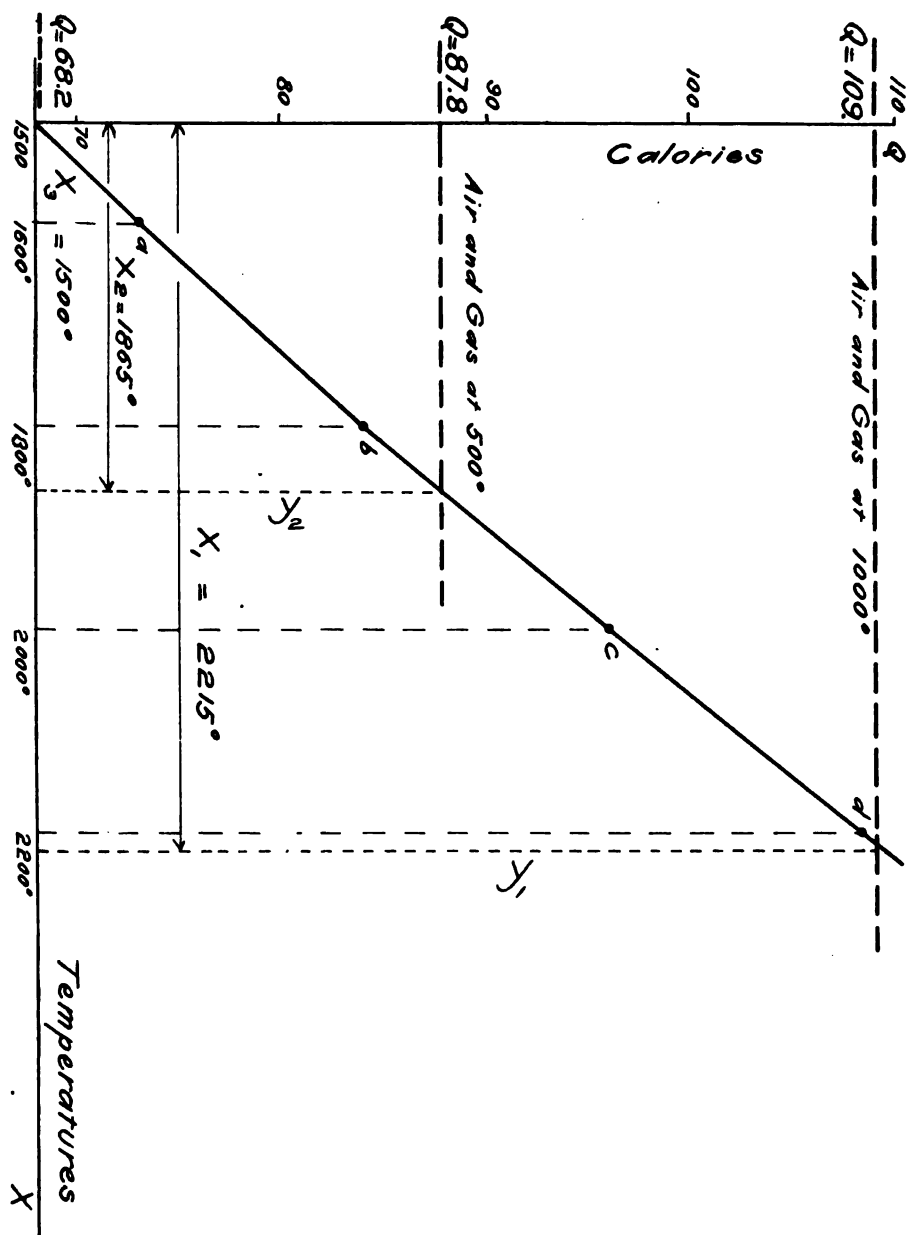


FIG. 6—TEMPERATURES OF COMBUSTION OF SIEMENS GAS ( $\text{CO} + 2\text{N}_2$ ).



If the air and gas are cold, the temperature of combustion falls to 1500°.

*Combustion Temperatures of the Pittsburg Natural Gas.*—We next seek to ascertain the temperature of combustion of the Pittsburg natural gas when burned with the theoretically requisite air, the air being burned cold; also, the temperature of combustion if the air is pre-heated to 1000° C.; further, the temperature of combustion of the same gas if 25% excess of air is injected in the furnace, the air being given, first cold and secondly pre-heated to 1000°.

The gas has the following composition, by volume:

CH <sub>4</sub> .....	67.00%
H <sub>2</sub> .....	22.00
C <sub>2</sub> H <sub>4</sub> .....	1.00
C <sub>2</sub> H <sub>6</sub> .....	5.00
CO.....	.60
CO <sub>2</sub> .....	.60
O <sub>2</sub> .....	.80
N <sub>2</sub> .....	3.00
Total.....	100.00%

Volume of oxygen required for combustion, and the resulting volumetric composition of the products of combustion:

Volume of Oxygen required		Volume of the Products of Combustion		
Gas	O <sub>2</sub>	CO <sub>2</sub>	H <sub>2</sub> O	N <sub>2</sub>
CH <sub>4</sub>	.67 × 2 ..... 1.34	.67	1.34	....
H <sub>2</sub>	.22 × .5 ..... .11	....	.22	....
C <sub>2</sub> H <sub>4</sub>	.01 × 3 ..... .03	.02	.02	....
C <sub>2</sub> H <sub>6</sub>	.05 × 3.5 ..... .175	.10	.15	....
CO	.006 × .5 ..... .003	.006	....	....
CO <sub>2</sub>	.....	.006	....	....
N	.....	....	In gas Brought by O <sub>2</sub> {	.03 6.28
Total.....	1.658	.802	1.73	6.31
Oxygen in gas.....	.008	....	....	....
Oxygen from the air.....	1.65	....	....	....
Nitrogen from the air.....	....	....	....	6.28
Total volume of air.....	....	7.93	....	....
If we introduce 25% excess of air, the volume of air becomes 7.93 + 1.98 =	....	9.91	....	....

The composition of the products of combustion in this latter case becomes:

	Molecular Volumes.
CO <sub>2</sub> .....	8.02
H <sub>2</sub> O.....	1.73
O <sub>2</sub> .....	.41
N <sub>2</sub> .....	7.85

Thermal capacities of the products of combustion, in the case of no excess of air:

Gas	Vol.	1800°	2000°	2200°	2400	3000°
N <sub>2</sub> .....	6.310	89.7	101.3	113.0	125.1	163.4
H <sub>2</sub> O.....	1.730	41.3	48.0	55.0	62.4	87.5
CO <sub>2</sub> .....	.802	21.8	24.5	29.3	33.4	47.1
Total.....	8.842	152.8	173.8	197.3	220.9	298.0

Calories brought by the air at 1000° C. (no excess of air):

$$7.43 \times 7.93 = 58.9 \text{ calories.}$$

Calorific power of the gas:

CH <sub>4</sub>	.67	× 195.2	.....	130.78	Calories.
H <sub>2</sub>	.22	× 58.2	.....	12.84	"
C <sub>2</sub> H <sub>4</sub>	.01	× 341.9	.....	3.42	"
C <sub>2</sub> H <sub>6</sub>	.05	× 321.77	.....	16.09	"
CO	.006	× 68.2	.....	.41	"
Total.....				163.54	Calories.

Total calories, sensible and latent, in the case of no excess of air:

$$58.9 + 163.54 = 222.44 \text{ calories.}$$

The intersections of the curve and straight lines give, as the temperatures of combustion, 2415° C. when the air is heated to 1000° C. and 1900° when the air is cold.

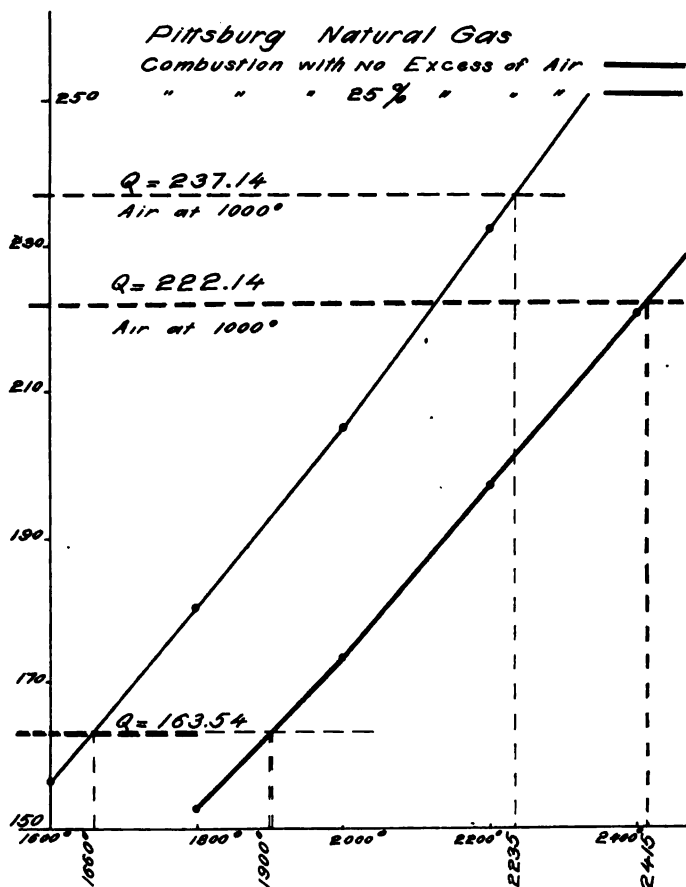


FIG. 7.

Thermal capacities of the waste products with 25% excess of air:

Gas	Mol. Vol.		1600°	1800°	2000°	2200°
N <sub>2</sub> .....	7.85	8.26	103.0	117.4	132.5	148.0
O <sub>2</sub> .....	.41		35.2	41.3	48.0	55.0
H <sub>2</sub> O.....	1.73		18.5	27.8	24.5	29.3
CO <sub>2</sub> .....	.802					
Total.....	↓.....	.....	156.7	180.5	205.0	232.3

Calories brought by the air at 1000° C.

$7.43 \times 9.91 =$ .....	73.60 Calories.
Latent heat of gas.....	163.54
Total.....	237.14 Calories.

From the diagram we find that the temperatures of combustion are respectively 2235° C. and 1660° C.

To what temperature should the theoretically required air be pre-heated in order that the temperature of combustion be 3000° C.?

The thermal capacities of the products of combustion at 3000° are 298.0 calories; the gas has a latent heat of 163.54 calories; therefore, the air must bring an extra number of calories equal to

$$298.0 - 163.54 = 134.46 \text{ calories.}$$

This is for the total air, which has a molecular volume equal to 7.93; the calories per molecular volume must be equal to

$$134.46 \div 7.93 = 16.97 \text{ calories.}$$

From the diagram of the thermal capacities we find at once that the air should be pre-heated to 2100° C.

*The Natural Gas of Iola, Kansas, contains by analysis:*

Methane,	CH <sub>4</sub>	.....	89.66% by volume.
Carbon Monoxide,	CO	.....	1.23
Carbon Dioxide,	CO <sub>2</sub>	.....	.90
Nitrogen,	N <sub>2</sub>	.....	7.76
Oxygen,	O <sub>2</sub>	.....	.45

Required:

(1) The temperature of combustion, if the gas is burned cold, with the theoretical amount of cold, dry air necessary.

(2) The temperature of combustion, if burned cold, with the requisite air pre-heated to 1000°. Also if pre-heated to 500°.

(3) The temperature of combustion, the gas being burned cold with 25% more air than theoretically necessary, the air being cold, pre-heated to 500° and to 1000°.

(4) The temperature of combustion, the gas being burned cold with a quantity of air smaller than theoretically necessary, so that 5% of the gas remains unburned. The air being cold, then pre-heated to 500° and finally pre-heated to 1000°.

## Calorific power of the gas per molecular volume (22.32 liters)

Calories per M. V.		
CH <sub>4</sub>	$.8966 \times 195.2 =$	175.0 Calories.
CO	$.0123 \times 68.2 =$	.84
Total.....		175.84 Calories.

## Molecular volumes of oxygen required for combustion:

CH <sub>4</sub>	$.8966 \times 2$	1.793
CO	$.0123 \times 0.5$	.0062
Total.....		1.7992
Oxygen in gas.....		.0045
Oxygen required from the atmosphere.....		1.7947

## Nitrogen carried by the oxygen:

$1.7947 \times 3.808 =$	6.836
Total volume of air.....	8.6307

## Composition of the products of combustion:

CO <sub>2</sub>	$.8966 + .009 =$	.9056
H <sub>2</sub> O	1.79	1.79
N <sub>2</sub>	$6.836 + .0776 =$	6.914

## Calories brought by air at 1000°:

$6.914 \times 7.43 =$	51.37
Latent calories of gas.....	175.84
Total.....	227.21

## Calories brought by air at 500°:

$6.914 \times 3.57 =$	24.68
Latent calories of gas =	175.84
Total.....	200.52

## Thermal capacities of the products of combustion:

Gas	Mol. Vol.	2000°	2200°	2400°	2600°
N <sub>2</sub> .....	6.914	110.95	123.85	137.20	150.08
H <sub>2</sub> O.....	1.74	49.70	57.07	64.77	72.71
CO <sub>2</sub> .....	.9056	28.83	33.20	37.82	42.71
Total.....		189.48	214.12	239.79	265.50
		a	b	c	d

The parabolic curve corresponding to the points *a*, *b*, *c*, *d* has been plotted in Fig. 8. Its intersections with the straight lines  $Q = 175.84$ ,  $Q = 227.21$  and  $Q = 200.52$  give the required tem-

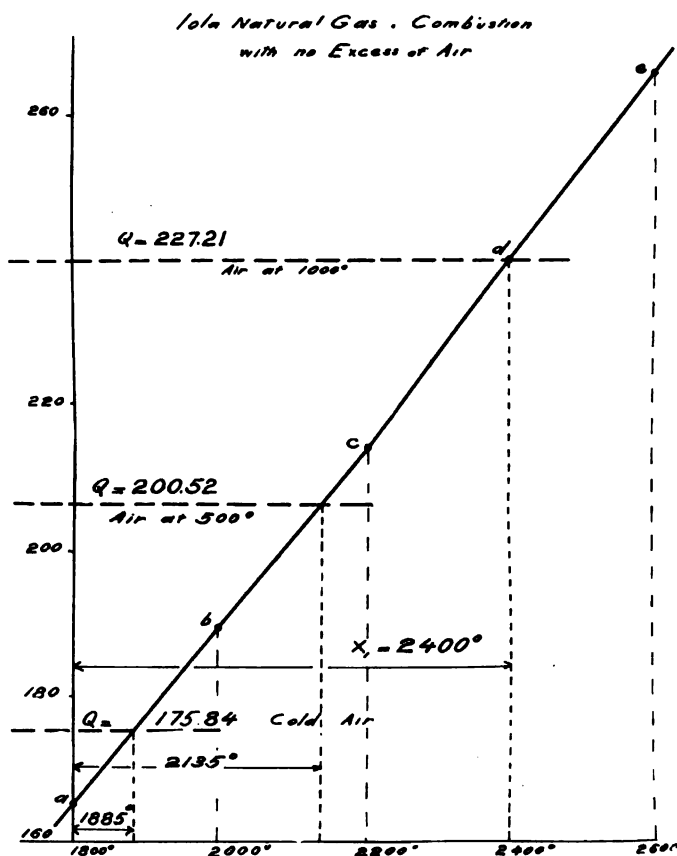


FIG. 8.

peratures of combustion, namely, 2400°, 2135° and 1885° respectively.

*Combustion with 25% excess of air:*

Free Oxygen, $1.79 \times .25 =$	.45	
Excess of Nitrogen.....	1.709	
Excess of air.....	2.16	Molecular Volumes.
Total volume of air.....	10.79	

Composition of the products of combustion:

N <sub>2</sub>	6.914 + 1.709 =	8.623
O <sub>2</sub>		.45
H <sub>2</sub> O		1.79
CO <sub>2</sub>		.91

Calories brought by air at 500°:

8.63 × 3.57 =	30.81
Latent heat of gas:	175.84
Total.....	206.65

Calories brought by air at 1000°:

10.79 × 7.43 =	80.2
Latent heat of gas:	175.84
Total.....	256.04

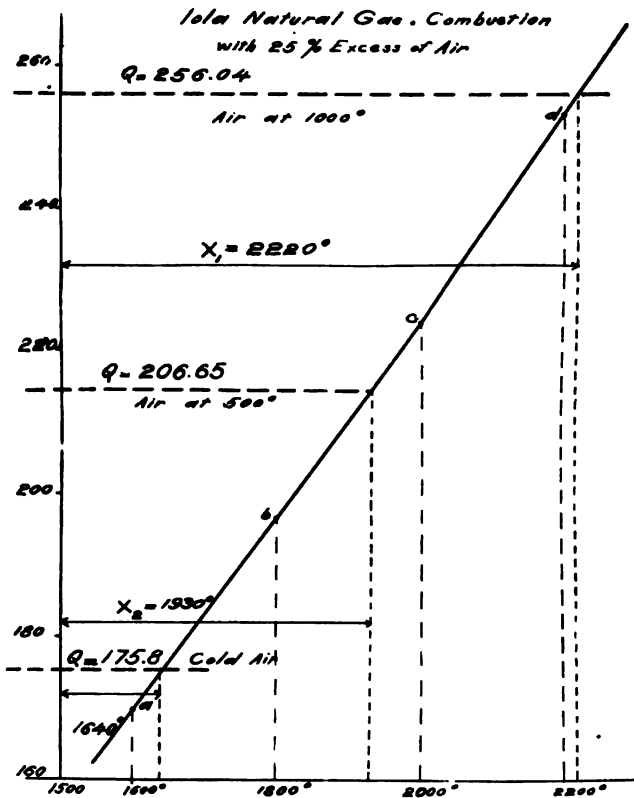


FIG. 9

## Thermal capacities of the products of combustion:

Gas	Mol. Vol.	1800°	2000°	2200°	2400°
N <sub>2</sub> .....	9.073	129.0	145.6	162.55	180.00
O <sub>2</sub> .....		42.72	49.70	57.07	64.77
H <sub>2</sub> O <sub>2</sub> .....		24.65	28.83	33.20	37.82
CO <sub>2</sub> .....	.91				
Total.....		196.37	224.13	252.82	282.59
		a	b	c	d

The intersections of the straight lines of which the equations are  $Q = 175.84$ ,  $Q = 206.65$  and  $Q = 256.04$  with the curve characterized by the points  $a$ ,  $b$ ,  $c$ ,  $d$  give the required temperatures, namely 1640°, 1930°, 2220°.

*Combustion with 5% of unburned gas:*

Calorific power	$175.84 \times .95 =$	167.1	Calories.
Oxygen required,	$1.79 \times .95 =$	1.7	
Nitrogen required,	$1.7 \times 3.808 =$	6.48	
Volume of air.....		8.18	

## Composition of the products of combustion:

CO <sub>2</sub>	$.8966 \times .95 + .009 =$	.86
H <sub>2</sub> O	$1.792 \times .95 =$	1.703
N <sub>2</sub>	$6.48 + .0776 =$	6.55
CH <sub>4</sub>	$.8966 \times .05 =$	.044

## Calories brought by air at 500°:

$8.18 \times 3.57 =$	29.2	Calories.
Latent heat of gas =	167.1	
Total.....	196.3	Calories.

## Calories brought by air at 1000°:

$8.18 \times 7.43 =$	60.8
Latent heat of gas.....	167.1
Total.....	227.9

## Thermal capacities of the products of combustion:

Gas	Mol. Vol.	1800°	2000°	2200°	2400°
N <sub>2</sub> .....	6.55	93.18	105.	117.3	130.
H <sub>2</sub> O.....	1.70	40.56	47.2	54.1	61.4
CO <sub>2</sub> .....	.86	23.40	27.38	31.5	35.9
CH <sub>4</sub> .....	.044	1.62	1.91	2.2	2.6
Total....		158.76	181.49	205.1	229.9
		a	b	c	d



In the usual manner, as shown in Fig. 10, we find the required temperatures of combustion to be as follows: 1875°, 2130°, 2385° C.

#### DISSOCIATION.

Until recently the thermal capacities were known to 100° C. only; these values were applied by an impermissible interpolation

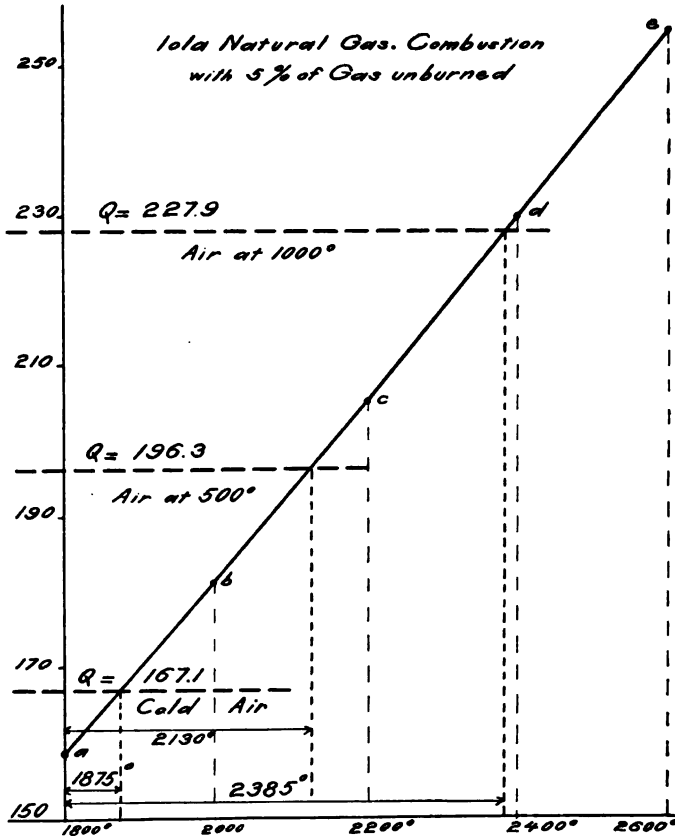


FIG. 10

to the calculation of the temperatures of combustion, and, naturally, very much higher temperatures were obtained.

In order to explain the discrepancy between theoretical figures and practice, physicists claimed that dissociation played an im-

portant rôle; that, by preventing the complete combination of the elements, the number of calories liberated was decreased, thus bringing the computed figures nearer the values obtained in practice. On the authority of Mallard and Le Chatelier, the phenomenon of dissociation, even at  $2000^{\circ}$ , is of little importance, as will be seen from the tables giving the results of their research.<sup>1</sup>

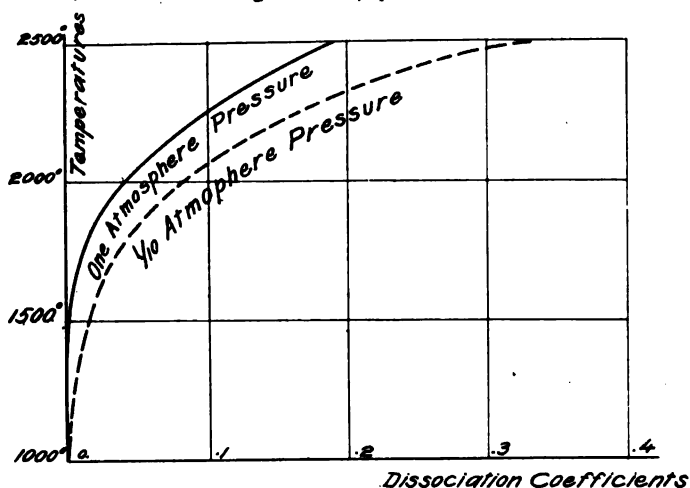
*Dissociation of Carbon Dioxide.*

TABLE 8.

DISSOCIATION OF CARBON DIOXIDE.

Temperatures $t = T - 273$	Coefficients of Dissociation	
	$p = 1$ Atmosphere	$p = \frac{1}{10}$ Atmosphere
$1000^{\circ}$ .....	0.0006	0.001
$1500^{\circ}$ .....	0.0008	0.017
$2000^{\circ}$ .....	0.04	0.08
$2500^{\circ}$ .....	0.19	0.33

L. Babu, "Traité de Metallurgie Générale," p. 220.

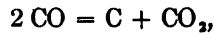
FIG. 11.—CURVE OF THE DISSOCIATION OF CARBON DIOXIDE,  $\text{CO}_2$ .

<sup>1</sup> Berthelot was the first to reject the importance of dissociation in combustion phenomena. He contested the probable value of the coefficients of dissociation when computed from the temperatures of combustion and the specific heats of gases between  $0^{\circ}$  and  $100^{\circ}\text{C}$ . He asserted the law of increase of the specific heat of gases, a law which the work of Mallard and Le Chatelier made evident.

*Dissociation of Water Vapor.*—The quantitative values of the factors of dissociation of water vapor have been determined by Le Chatelier. They are very close to those given for the dissociation of carbon dioxide.

It is, then, entirely permissible, both in our preceding calculations and the theory of furnaces which is to follow, to overlook the dissociation factor—of which, however, account might be taken, since the products of combustion are formed of carbon dioxide and water vapor, and the industrial temperatures are lower than 2000° C.

*Dissociation of Carbon Monoxide.*—The dissociation of this gas represents remarkable peculiarities. Its decomposition into Carbon and Carbon Dioxide, according to the reaction



is a maximum and almost complete at 450° C., but decreases to almost nothing at 1000° C.

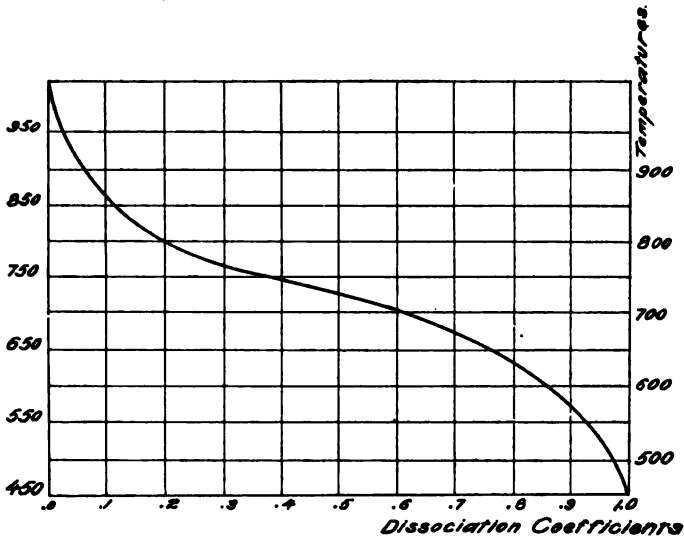


FIG. 12.—CURVE OF THE DISSOCIATION OF CARBON MONOXIDE, CO

TABLE 9.

## DISSOCIATION OF CARBON MONOXIDE.

Temperatures	Condensation		Coefficients of Dissociation at Atmos. Pressure
	of CO = C <sub>1</sub>	CO <sub>2</sub> = C <sub>2</sub>	
450°.....	0.02	2.98	1.00
500°.....	0.05	0.95	0.97
600°.....	0.23	0.77	0.87
700°.....	0.58	0.42	0.59
800°.....	0.90	0.10	0.182
900°.....	0.965	0.035	0.067
1000°.....	0.993	0.007	0.013

L. Babu, "Traité de Metallurgie Générale," p. 227.

This phenomenon plays an important rôle in the running of gas-producers. It explains why it is impossible, especially at low temperatures, to obtain carbon monoxide free from carbon dioxide, which is the rule in lean industrial gases.<sup>1</sup> It explains, also, the deposit of soot in the pipes and exits of producers. To it will be due, in our general study of furnaces, the most important source of variation between theory and practice.

<sup>1</sup> This has a very important bearing on the practical operation of gas-producers.—*Translator.*

## CHAPTER II.

### PROGRESS IN INDUSTRIAL HEATING—CLASSIFICATION OF THE DIFFERENT SYSTEMS OF GAS FURNACES—THEIR ORIGIN AND DEVELOPMENT.

The number of gas furnaces in practical use today is so large that it is necessary to classify them before we can take up their general theory. We will take advantage of this to trace briefly the progress realized from the origin of gaseous fuel, or rather since the introduction of the method for the gasification of the fuel. It is this method that has transformed the problem, by opening the way to improvements not possible with direct fire furnaces.

*Origin and Rapid Development of Gas Furnaces.*—Gas furnaces, which are most essential to modern industry, are of recent invention. Their origin dates back to the patents granted Frederick and William Siemens in 1856 and 1861. Doubtless, in the older industries it is possible to find approaches to gas firing. In Wales, gas-producers were used from the time of coal mining. The metallurgists of that country used to carry a bed of coal of 60 to 80 cm. on their grates, in order to lengthen the short anthracite flame, for heating their rather large reverberatory furnaces.

Even the inversion, the basis of the Siemens regenerators, had been tried in the first hot-air motors. The idea of pre-heating the air necessary for combustion had been realized in some blast furnaces and in Ponsard and Bicheroux furnaces.

But all these scattered ideas gave only insignificant results, until Sir William Siemens (who united an admirable perseverance to his engineering genius) succeeded, after twenty years of study, in giving the problem of furnaces a solution so perfect that thirty years have added practically nothing to it, certainly no new principles.

The original Siemens Furnace is too well known to require de-

scription. Let it suffice to recall that, designed for the fusion of steel on an open hearth, it included a reverberatory with a very low arch. Its chambers were four in number, allowing the pre-heating of the gas and partial heating of the air; the inversion was effected by means of valves; the gas-producers, located at a certain distance from the furnace, were connected with it by a sheet-iron flue shaped like an inverted siphon. The draught of the producer was induced by the inequality in the length of the vertical legs.

This type of furnace was introduced first in metallurgical works; its progress was impeded for a time, between 1867 and 1871, by

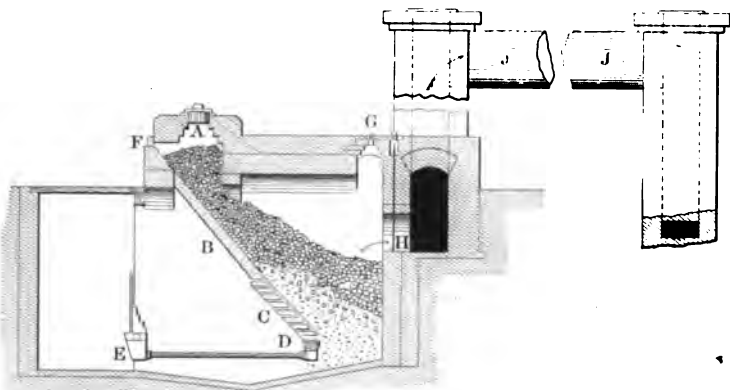


FIG. 13.—SIEMENS GAS-PRODUCER WITH SIPHON.  
(From D. K. Clark's "Fuel.")

the appearance of the Bessemer process; thereafter it grew very rapidly. It was first tried successfully in 1867 in plate-glass works at St. Gobain. However, it was not adopted by the plate-glass industry until 1876, after the tank furnace had given good results.

Today the gas furnace is in general use in metallurgy, in the glass, gas, and by-products coke industries; also, though rarely, in ceramics. It is the general tendency to introduce it in all industries requiring high temperatures, consuming large quantities of coal.

Its success is partly due to the advantages inherent in gas firing, easy regulation of combustion, which can be made perfect without excess of air, the possibility of a long flame and therefore of large furnaces, and last, but not least, the use of fuel of inferior quality. Its success is largely due also to the original perfection of the furnace, and the fact that regeneration permits high temperature as well as economy.

It is readily admitted, after reviewing the successive transformations which have made perfect the first solution and seeing all the parts of the primitive furnace, one after the other, improved, that one of the greatest merits of the gas furnace is, that it has made a distinction between the various functions required for industrial heating, and has applied to each of them an especial organ. The well defined function of each facilitated their regulation. This advantage of gas-fired furnaces has often been lost sight of.

In the older methods of heating everything was confused; the old glass-pot furnace gives a striking example. It was formed of a hearth, containing the pots, placed above the fire-grate, without a stack; the draught was susceptible of regulation only by variation in the depth of the fuel on the grate. Under such conditions, firing was truly an art. Today, in a gas-fired furnace the grate, the hearth, the chimney, and the new organ, the recuperator, are distinct. Each may be controlled in a methodical way. Thus it is often possible, even in the absence of skilled workmen, to avoid accidents and to ascertain the cause of those that may take place. The art of the skilled furnaceman, often so difficult to obtain, has given way to the science of the engineer, the acquisition of which is always possible.

The distinction made in the various furnace organs has had still further the advantage of opening wide the door to progress. While in the old industry the lines of furnaces were transmitted generally by tradition, without attempt at alteration, even in the least particular, for fear of disaster, today inventors have tried to improve each and all of the organs, and they have been able to do so with the utmost satisfaction. Thus, without any single great improvement, gas-fired furnaces have gradually become perfected.

These improvements will be reviewed in the case of each organ. Their enumeration is the only classification that can be undertaken until a theory of combustion has been formulated which allows the only rational classification—that based on the heat utilization.

#### DESCRIPTION AND FUNCTIONS OF THE ESSENTIAL PARTS OF GAS FURNACES.

A gas furnace has in general the following parts:

(1) *The gas-producer*, in which combustible gases are generated by the incomplete combustion of the fuel, by means of a first introduction of air—the PRIMARY AIR. This organ may have complete autonomy, its own draught apparatus (Siemens siphon, etc.), or it may form a close part of the furnace and depend upon its chimney.

(2) *The inversion valves*, which consist of butterfly or bell valves; their function is to direct to one side or the other the products of combustion and the gases required for the firing of the furnaces. These valves do not always exist—for example, in furnaces where the heat of the products of combustion is recuperated by means of the counter parallel current system; when they do exist (as in the Siemens furnace), they are the exact division line between the regenerative chambers and the chimney on the one hand, and the recuperative chambers and the gas-producer on the other. This exact limitation of the chambers and of the gas-producer, which we give as a definition, appears the most rational, both from the theoretical point of view and for the practical control of the furnaces. In the study of a furnace, the gas-producer should not be limited to the space where the fuel is gasified, but should be made to include also all pipes and flues, whatever their length, leading to the entrance of the chambers. The gas-producer is made responsible up to the moment that it delivers the gas to the recuperative chambers. It is with this extended but well defined meaning that the word “gas-producer” is to be understood here.

(3) *The chambers of recuperation*, whose function it is to utilize or to bring back, so to speak, to the furnace those calories which otherwise would be carried away by the products of combustion.



The chambers begin at the distributing valve, where the producer ends, and terminate exactly at the entrance to the furnace, by the ports where the combustion begins; they include, therefore, the ports of the gas and of the air.

(4) *The laboratory or furnace proper or hearth*, where the industrial operation is effected, and where the combustion of the fuel is completed by a new influx of air—the SECONDARY AIR. The laboratory is limited by the ports of admission and of escape.

(5) *The chimney*, or the draught apparatus taking its place, for the purpose of discharging into the atmosphere the products of combustion, and of insuring at the same time the circulation of the various gas currents, either simply from the hearth to the stack or onward from the gas-producer. The stack begins where the chambers end, that is, at the distributing valves. The chimney is completed, as far as the draught is concerned, by a certain number of dampers, or their equivalent, at the various flues of admission or exit.

These regulating devices, which are distributed throughout the various parts of the furnace, are of the greatest importance, and in general, the greater their number, the more easily will the furnace be controlled. In order to show their usefulness, we will classify the various currents of gases which circulate in a complete gas furnace.

(a) In the gas-producer a certain quantity of air is admitted—the primary air, which must be regulated by means of a damper or an injector.

(b) In its journey through the producer the primary air gasifies the fuel, transforming it into a mixture of  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{H}_2$ ,  $\text{H}_2\text{O}$ , etc.; this is the producer-gas.

(c) At the entrance to the hearth the gas meets a new afflux of air, the secondary air.

(d) The products of combustion are divided into two parts, one going to the gas recuperators, the other to the air-chamber. It is of prime importance to regulate this division, since it has a most important bearing on the ruling temperature of the hearth.

(e) Finally, the two currents of the waste products meet at the base of the stack, to be consigned to the atmosphere. It is also

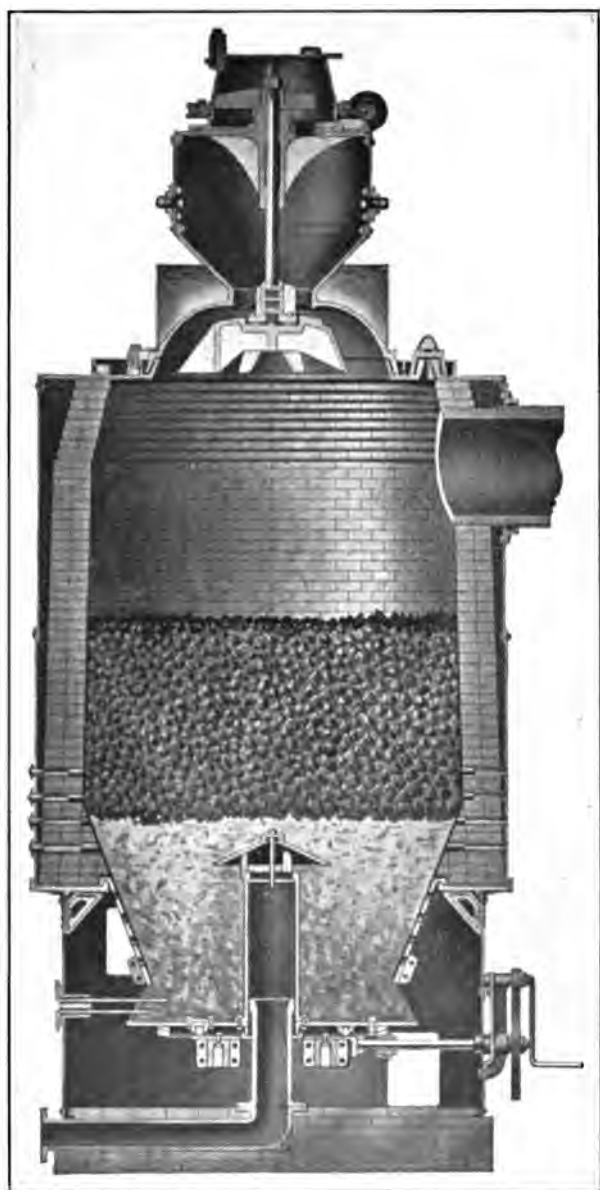


FIG. 14.—TAYLOR GAS-PRODUCER, WITH MECHANICAL FEED.

useful to be able to regulate the draught of the stack, since the pressure in the hearth is a function of the chimney draught.

The importance of the multiplicity of dampers is easily seen from the foregoing. The first Siemens furnace had only two or three, while the more recent furnaces have not less than four—two at the admission, and two at the exit.

#### MODIFICATIONS AND IMPROVEMENTS EFFECTED IN GAS FURNACES.

(1) *Gas-Producers*.—The question of gas-producers has been the most studied. The Siemens inclined grate has given place almost everywhere to producers with horizontal grate, or even without a grate at all. The inclined grate had the advantages of distributing the coal along a talus parallel to the face of the producer and of facilitating its equal distribution in a deep bed, of closing up at each feeding the blow-holes that the combustion had produced, and of requiring less skilled labor. Such, at least, was the idea advanced by its inventor.

The horizontal grate, on which is placed a bed of 80 to 120 cm. or more of fuel, requires the close attention of the workman; he must also distribute the coal evenly at each feeding, as well as break up any blow-holes formed. It has, however, a much higher efficiency than the inclined-grate type.

Let us here also note the trials of grateless producers. This type is very interesting, since it allows the thorough pre-heating of the primary air—the last desideratum of the furnace problem. The St. Chamond steel works operate gas-producers without any grate in which the coal places itself along its angle of repose; but they do not seem to be preferred to producers provided with grates.

The best form of the grateless producer is the Taylor, with its rotating hearth. Here, however, the injected steam and air cannot be pre-heated, or have not been pre-heated, above 400°.

Lastly may be mentioned the Ebelmen fusion producer, in which the ashes are fluxed and fused. This idea, though very attractive, has been practically applied to no large extent.

It is chiefly in perfecting methods of gasification that inventors

have tried to obtain a gas richer than the Siemens gas. It may be said in general that the Siemens gas carries 5% or more of carbon dioxide, a rather high proportion, which lowers greatly the calorific power of the gas, due partly to the dissociation of carbon monoxide

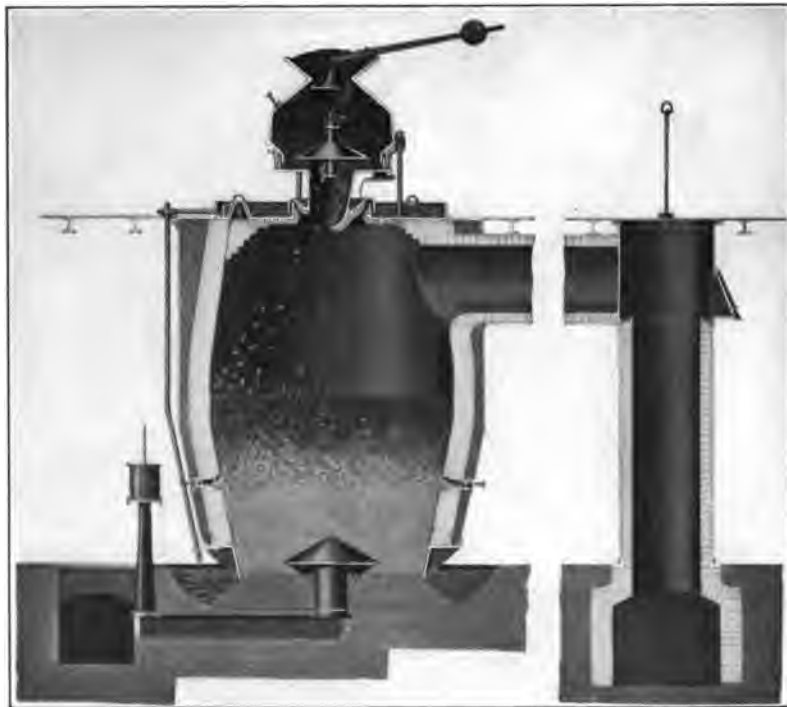
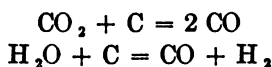


FIG. 15.—MORGAN GAS-PRODUCER, WITH MECHANICAL FEED.

(see page 36). This appears difficult to overcome; nevertheless, many inventors have attempted it.

The Siemens gas, generated by means of the atmospheric air, carries a weight of nitrogen which is harmful in all combustion reactions. Many have tried to eliminate this nitrogen by gasifying the fuel with a gas other than the air; for instance, by steam

or even carbon dioxide, which reacts at a red heat on the carbon according to the well-known reactions



It will be seen further on that the industrial production of pure water gas, in practical and simple apparatus, is not possible,<sup>1</sup>

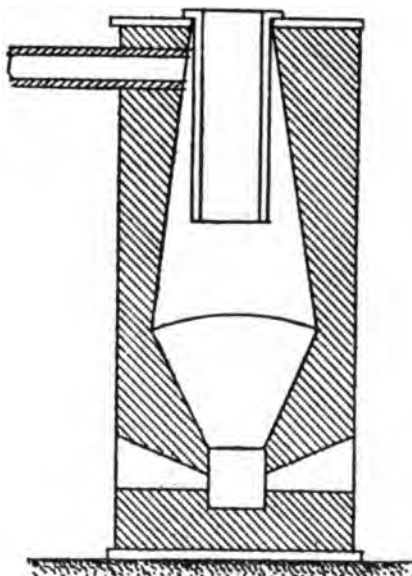


FIG. 16.—EBELMEN GAS-PRODUCER.  
(From A. H. Sexton's "Fuel.")

<sup>1</sup> Great progress has been made in the last few years in the manufacture of water gas, through the introduction of the Dellwick process and apparatus (Fig. 19). In the old process, air is blown through the fuel bed, as in the usual producer, until the fuel reaches a bright red heat, the coal being oxidized to CO, and producer-gas formed. At this point, the air is shut off and steam injected. Water gas is generated at the expense of the sensible heat of the fuel. When the lowest temperature limit is reached the steam is shut off and air admitted, the cycle of operations being repeated. In the first period, only 29.4 calories are liberated per molecule of carbon gasified to CO, and in the second 28.8 calories are absorbed. It follows that the times of the two periods must practically be equal, usually 10 minutes. Dellwick devised to oxidize the coal not to carbon monoxide, but at once to carbon dioxide, the heat liberated, in this case, being 97.6 calories per molecule of carbon. The calories are then as  $\frac{97.6}{29.4}$ ; or about 3.5 to 1. In practice, the air is injected for  $1\frac{1}{2}$  minutes and the steam for 8 to 10 minutes, a great difference in time. The apparatus is also much simplified, the gas on the air phase being allowed to escape to the stack; one gas-holder is then sufficient. The thermic efficiency is also much improved. The combustion of the coal to CO<sub>2</sub> is obtained by means of the injection of air under high pressure—300 mm. or more of water.—*Translator.*

and that the so-called regeneration of the carbon dioxide of the products of combustion, according to the ideas of Biedermann, Harvey, and many others, is always unnecessary and often harmful. Nevertheless, furnaces have been constructed and are operated on these principles, and they will be described further on.

TABLE 10.  
ANALYSIS OF VARIOUS INDUSTRIAL GASES.

	Mixed Gas									Riché Gas (Wood)		Mond Gas	
	Anthracite	Anthracite	Anthracite	Anthracite	Bituminous	Bituminous	Bituminous	Bituminous	Coke			Without NH <sub>3</sub> Recovery	With NH <sub>3</sub> Recovery
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
H <sub>2</sub> .....	17.31	18.31	20.75	20.0	10.0	18.73	14.0	14.0	10.0	45.0	12.2	27.5	24.3
CH <sub>4</sub> .....	.....	.....	.....	.....	3.0	0.31	0.4	.....	.....	15.0	3.4	2.0	2.0
C <sub>2</sub> H <sub>4</sub> .....	.....	.....	.....	.....	0.5	0.31	.....	.....	.....	.....	1.0	.....	.....
CO.....	22.39	21.54	20.63	25.0	23.0	25.07	26.0	27.20	29.0	20.0	11.6	11.0	13.8
CO <sub>2</sub> .....	8.36	9.50	10.41	5.0	5.0	6.57	6.9	5.50	4.5	20.0	9.3	16.5	13.9
N <sub>2</sub> .....	51.94	50.65	48.22	49.5	58.0	46.98	52.8	53.30	56.0	.....	62.5	43.0	46.0
	H <sub>2</sub> O											N <sub>2</sub> +H <sub>2</sub> O	
O <sub>2</sub> .....	4.04	3.37	5.02	0.5	0.5	0.03	.....	.....	0.5	.....	.....	.....	.....

1, 2, 3, 8, 17, 18, 21, 30. A. L. Queneau.

4, 5, 9, 12, 13, 19, 22, 23, 24, 25, 28. W. L. Case. J. S. C. I., June 15, 1905.

6. Dowson, *The Engineering and Mining Journal*, XXXIX, page 418.

7. Fisher-Gautier, "Essai des Combustibles"; gas from a Klönne Gas-Producer blown with air and steam.

10, 11. C. Vigreux and L. Bardolle, "Le Gas Riché, ses Applications Industrielles."

If the pure water gas is not practical, the mixed gas—a mixture of Siemens and of water gas—is widely used, and has, in some systems of recuperation, some very real advantages.

The mixed gas is obtained either by blowing steam in the producer provided with a closed ash-pit, or by keeping the ash-pit filled with water. In the latter case, the fall of the clinkers and the radiated heat are sufficient to produce a large vaporization, giving as high as 12% of hydrogen in the producer-gas. Of all systems of gasification, the one of the mixed gas is by far the most used.

A recent improvement made in the construction of gas-producers is the bettering of the draught. When steam is injected by means of a Koerting steam injector, this apparatus furnishes at the same time the required air. Thus, the Siemens siphon may be dispensed with. This doing away with the siphon takes

place even now in the case of producers provided with natural draught. For this purpose it is sufficient to place the producer at a lower level than the furnace, in such a way that its grate will be at a certain distance below the level of the ports. The rising column of hot gases acts as a chimney. This is an important

TABLE 10. (Concluded.)

ANALYSIS OF VARIOUS INDUSTRIAL GASES.

Siemens Gas				Water Gas				Retort Gas	Oil Gas	Carbureted Water Gas	Coke Oven Gas	Methane-Hydrogen Gas	Dellwicks Water Gas	Blast Furnace Gas		
14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.	29.	30.
6.5	1.9	.....	2	1.48	0.48	5.48	5.46	0.32	0.40	0.50	0.58	7.0	1.0	1.0	3.6	3.68
1.9	.....	.....	2.0	2.0	0.5	0.5	0.5	40.0	48.0	25.0	36.6	10.0	0.2	.....	.....	3.62
23.7	29.4	30.9	34.1	33.8	38.0	40.4	43.6	5.0	16.5	8.5	4.0	1.3	0.0	.....	.....	.....
6.3	2.3	3.3	8	1.3	6.0	5.2	3.4	0.5	.....	3.0	1.5	10.0	4.65	11.5	9.0	6.15
62.6	66.7	66.7	64.9	64.8	5.5	5.6	4.0	2.0	3.0	4.0	2.0	.....	3.83	60.0	51.3	59.27
.....	.....	.....	.....	0.5	.....	.....	.....	0.5	0.5	0.5	0.5	.....	0.20	.....	H <sub>2</sub> O 10.0	.....

14, 15, Fisher-Gautier, *loc. cit.*, is from a Klönne Gas-Producer blown with air alone.

18, Shabel-Gautier, "Traité de Métallurgie Générale."

20, Leybold, *Journal für Gas Beleuchtung*, 1898, page 1528.

26, *Journal Gas Lighting*, page 90, 1905.

27, Fisher-Gautier, *loc. cit.*

29, Lürman, *Stahl und Eisen*, page 245, 1898.

advantage, especially in the case of glass furnaces where, on account of the constant opening of the working doors, the chimney has no effect on the producer.

It is seen that we have to discuss furnaces fired with three different gases—Siemens gas, mixed gas, and gas produced by the so-called regeneration of the carbon dioxide of the products of combustion.

(2) *Regenerators or Recuperators*.—The least progress has been made in the question of heat recuperation. Two systems are still in practice—the Siemens recuperator with inversion, and recuperation without inversion, by parallel counter currents.

In the first system, the heat of the products of combustion is accumulated in a network of firebricks, through which the waste products are made to circulate. These bricks will give back their accumulated heat to the cold air and gas, which will flow through them in a reverse direction at the succeeding inversion. In the second





proportions have been greatly modified; thus, the gas chambers have been reduced to one-half of their original volume, and the latest tendency is to dispense with them altogether. From the point of view afforded by theoretical study, the method of recuperation is less important than the way in which it is applied.

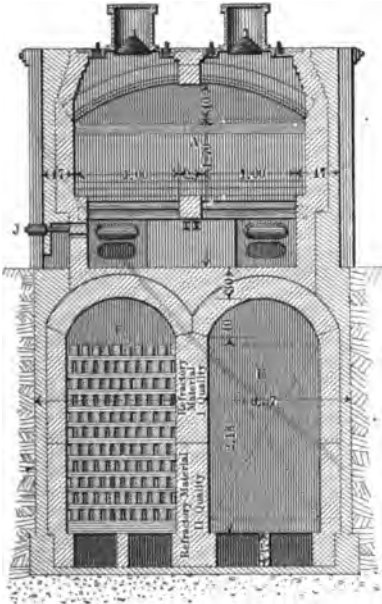


FIG. 17a.—SECTION E F.

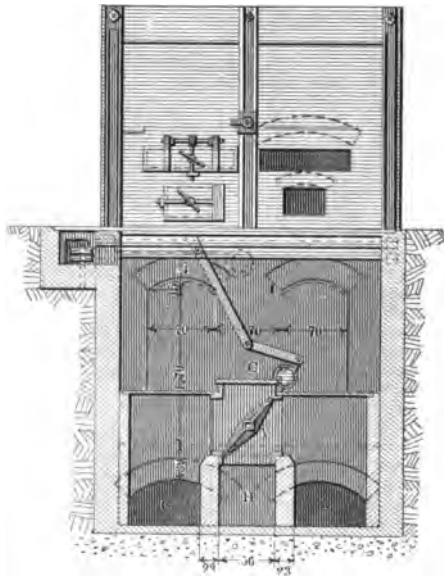


FIG. 17b.—SECTION G H.

Four different ways present themselves:

- (a) Pre-heating of the secondary air alone.
- (b) Pre-heating of the secondary air and of the gas.
- (c) Pre-heating of the total air—primary and secondary.
- (d) Pre-heating of the secondary air, primary air and gas.

(3) *Furnace proper, or Hearth.*—The form of gas-fired reverberatory furnaces has undergone two important modifications—first, as regards the roof, it being made very high (in some new radiation furnaces there are 250 cm. between roof and the hearth); and next, as to the disposition of the ports, in the so-called horse-



recuperation, we believe it to be better to use the older style of hearth with the flames crossing from end to end.

Such are the main transformations that the Siemens furnaces and gas firing have undergone. From the point of view of the

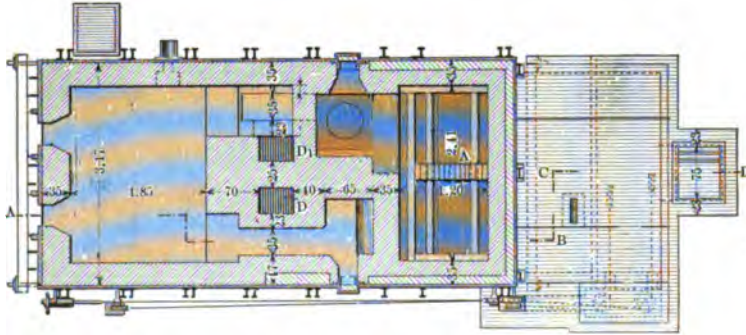


FIG 17d.—SECTION L M.

general theory, which is taken up in the succeeding chapters, we must remember that the four methods of heat regeneration may be applied to the following three different producer-gases:

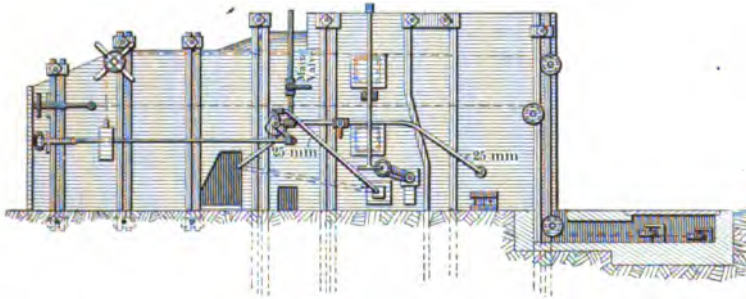


FIG. 17f.

- (a) *Siemens gas*, mixture of carbon monoxide and nitrogen.
- (b) *Mixed gas*, mixture of carbon monoxide, hydrogen and nitrogen.
- (c) *The so-called regenerated products of combustion*, of about the same chemical composition as the mixed gas. There would thus

be twelve cases, if, as will be seen later, one case was not impossible.<sup>1</sup> There will be eleven cases to be examined, and it will be seen that all of them have received either full or partial application.

To illustrate the modifications of the original Siemens furnace we may give as a type the New Siemens furnace, which unites a majority of the improvements. This furnace is fired with mixed gas, the producer being blown with steam; it has double regeneration—that of the total air, primary and secondary, with a single pair of recuperative chambers, without siphon; the producer is built right against the furnace, and the hearth is horseshoe in shape.

We do not wish to say that this furnace is the best; still less do we desire to defend the so-called regeneration of the carbon dioxide contained in the combustion products, because theory will give us its exact value; but from the above enumeration it is easy to see that this new furnace has many of the aforementioned modifications which, applied individually, have given good results.

<sup>1</sup> The case of the triple recuperation with the Siemens gas.

### CHAPTER III.

#### PURPOSE OF THE THEORY OF RECUPERATION<sup>1</sup>—FUNDAMENTAL EQUATIONS OF HEAT UTILIZATION—DATA, HYPOTHESES, AND GENERAL PRINCIPLES.

*Influence of the Temperature on the Heat Utilization in a Furnace.*—The study of the progress made in industrial heating, which was considered in the preceding chapter, led us to a classification of eleven systems of gas-fired furnaces—furnaces with single, double (itself subdivided into two classes), and triple recuperation. The furnaces may be fired with Siemens gas, mixed gas, and gas resulting from blowing the producer with air, steam and products of combustion. Direct firing should also be included; though rarely used for high temperatures, it is common for moderate ones, but is used almost wholly for low temperatures, as, for instance, boilers. This forms a twelfth case to be treated.

This classification may appear quite complex when applied to forms of apparatus which, with the exception of direct-fired furnaces, are called indiscriminately gas furnaces, but which are often in reality Siemens furnaces. This is, however, almost the exact state of industrial conditions, from which will be taken some ten cases as illustrations of the different classes.

The multiplicity of expedients, tried and remaining in use, for solving a problem apparently capable of a single solution is partly due to the present difficulty in establishing the relative value of the various systems. It is also due to the high cost of construction of gas furnaces and to the difficulties attending their successful introduction. Hence, the hesitation exhibited by managers of works in substituting a perfected and more economical furnace in place of an older type in good working condition.

<sup>1</sup> Throughout this treatise we will take the word "recuperation" in its general sense, without discriminating between Siemens and parallel counter-current recuperation, unless otherwise specified.—*Translator.*

It is not uncommon to see in works several types of furnaces in operation.

The problem is complex and permits of several solutions according to the nature of the work to be accomplished, the length of the operation, the temperature, the condition of the draught, the nature of the fuel, its cost, etc. The general theory, which we will present, may be used as a guide, though its requisites may be overruled by economical considerations. All disturbing factors cannot be touched upon here.<sup>1</sup> There is one, however, more important than any other, which cannot be omitted in a theory of heat recuperation; it is the ruling temperature of the hearth.

*The ruling temperature* is that temperature best suited to the operation to be performed in the hearth. In a general theory this temperature is arbitrary, as the same type of furnace may be used in various industries and at widely different temperatures. In actual practice, however, this ruling temperature is selected to give the best results. It should not vary in continuous furnaces, and if it is subjected to fluctuations in intermittent work (as puddling furnaces, zinc furnaces, etc.), it should be regulated entirely with regard to the work to be done. It is in any case a condition to be established first in the experimental study of a furnace.

The ruling temperature has a considerable influence on heat utilization. It is evident that the waste products escaping from a furnace at, say, 1500° carry away, for a given weight of consumed fuel, more calories than when leaving at 300°, as in the case of boilers. Recuperation applied to these two cases will doubtless recover the calories, but only in part, allowing the remainder to escape to the stack. The absolute value of the latter will be the greater the higher the original number of calories in the waste gases, that is, the higher their original temperature. It follows that the lost heat and, by difference, the utilized heat, are functions of the temperature. It is also clear without any calculations that the law of efficiency, for furnaces operated under similar conditions, is a continuous function of the temperature, so that it would be possible to plot for each of the twelve furnaces its curve

<sup>1</sup> In order to make more interesting a theory rendered rather long by the complexity of the industrial cases, we will endeavor, when the discussion leads to it, to derive practical conclusions from figures, and thereby to elucidate a number of these particular cases

of heat utilization, the examination of which, at any temperature, would permit us to judge the relative value of each of them at a given temperature.

In order to avoid undue complexity, we have deemed it advisable to select two fixed temperatures— $1000^{\circ}$  and  $1500^{\circ}$ . The first corresponds to the temperatures of coke ovens, which may be taken as the type of industry using medium temperatures; the second is lower than the ruling temperatures of steel furnaces, while it is higher than that of the glass, ceramic and zinc industries. It will be easy by interpolation or extrapolation to find the efficiency at any other temperature. Thus limited, our general theory has a threefold object:

(1) To study the utilization of heat in the twelve systems in order to classify them at the two temperatures of  $1000^{\circ}$  and  $1500^{\circ}$ .

(2) To show the influence of the temperature on the efficiency, by comparing the heat utilization of the different systems, at the arbitrarily selected temperatures.

(3) To indicate the method of calculation which permits of ascertaining, for any given temperature, the comparative efficiency of the various furnaces, and to make the best selection.

*Definitions: Heat Utilized, Heat Lost, Efficiency, Equation of the Utilization of Heat.*—We must still define closely the meaning of "efficiency," "heat lost," and "heat utilized," and justify these definitions just as we were obliged to in the case of the various parts of the furnaces, and to justify the precise limits given them.

We understand, by "heat utilized" in a furnace, the whole of the heat consumed in the hearth, either in the performance of the industrial work, by exterior radiation (often necessary to preserve the brickwork), or heat completely lost by conductivity or any other cause. So defined, the utilized heat is exactly the difference between the total heat (sensible or latent) brought into the hearth by the secondary air and gas and the total heat carried away by the waste products.

By "heat lost" we understand all heat spent outside the hearth; that is, liberated into the atmosphere by the waste products, radiated or conducted by all organs other than the hearth (by the producer, the chambers, the flues, etc.), or consumed in the

vaporization of the water in the ash-pit, or used in producing the draught, etc.

Under these conditions it is evident that the sum of the lost heat and of the utilized heat represents the total heat absorbed in the furnace; that is, the total heat liberated by the fuel, or, in other words, its calorific power.

Our definition is then expressed in the equation:

$$Q = P + U$$

in which

$Q$  = The calorific power of the fuel.

$U$  = utilized heat; that is, heat consumed in the hearth.

$P$  = Lost heat; that is, heat carried away to the stack or lost by all parts other than the hearth.

Finally, by recuperative efficiency we understand the ratio  $\frac{U}{Q}$  of the heat spent in the hearth to the calorific power of the fuel.

These definitions give to heat utilized and heat lost a more comprehensive meaning than their usual one. Generally the only lost heat considered is that carried away by the waste products. By utilized heat is understood the heat necessary to the chemical reaction or to the physical operation to be effected—melting of the glass, or reheating of the ingots.

Our definitions are justified by the purpose of our study, which is recuperation. The object of recuperation being to collect all the heat not made use of in the hearth, the recuperative organs are responsible for the heat which is turned over to them, and they should restore it as completely as possible. If the restitution is done imperfectly, it does not matter whether the losses are to be charged to the liberation of the waste products into the atmosphere, or to the chambers of recuperation, or even to the radiation of the producer flues, for all these organs are agents of recuperation.<sup>1</sup> The total loss alone is of interest in determining the efficiency of a furnace.

<sup>1</sup> This remark has a practical interest; it often happens that the system of recuperation is estimated by the temperature of the stack. This datum is of minor importance, however, for the waste products might have lost a large quantity of heat by radiation, or by becoming mixed with cold air, without any advantage resulting to the hearth.



That which Ledebur calls "the useful effect," and which is the heat really utilized, is not, in a theory of industrial heating, of as great an interest as it might appear. In most cases, the masses to be heated (crucibles, retorts, muffles, furnace walls, etc.) have a specific heat much higher than the specific heats and the heats of reaction of the bodies under treatment. Often the heat of reaction is but a small fraction of the heat consumed in the hearth. It happens even, as an extreme case, that an exothermic reaction can take place only at a high temperature, so that in reality the heat utilized is *nil*, however perfect the furnace. In such a case, the calculation of the absolute efficiency or useful effect would be without any interest.

Furthermore, the recuperation we are studying does not take into account the manner in which the calories are spent and distributed in the hearth; it concerns itself only with the calories escaping from the hearth, and which it should bring back there.

To justify further our definitions, let us notice that, in the comparative study of the different types of furnaces, it is our perfect right to suppose that the hearth conditions are the same for all. The ruling temperature being invariable, it follows that the ratio between the utilized heat and the useful effect is invariable, and that, knowing one of the terms, the other may be ascertained. The calculation of the recuperative efficiency  $\frac{U}{Q}$  will give, therefore, the measure of the relative value of the furnace, considered from the point of view of the utilization of heat as well as of the useful effect.

Evidently all the preceding definitions apply as well to experimental tests of furnaces as to the theoretical determinations. In the case of experimental tests, the idea of the utilized heat is of great importance, since it can be reckoned by means of temperatures and of gas analyses; while, in general, the heat used for the industrial operation—the useful effect—can be computed only by the help of the specific heats and of the heats of reaction of the bodies present.

FUNDAMENTAL PRINCIPLES OF THE UTILIZATION OF HEAT IN FURNACES.—The study of the utilization of heat in furnaces is

controlled by a few fundamental principles so evident that it would be superfluous to recall them if some of their most immediate deductions had not been either misunderstood or forgotten. It is only by keeping in mind these self-evident truths, comparable to the principles of thermo-dynamics, that the errors of calculations or of reasoning, so easily made, will be avoided in the question of the exchange of calories, sensible or latent, and of recuperation in which the available heat is several times transformed.

(A) *Principles Relating to Combustion and to the Total Available Heat.*—(1) In a gas furnace the source of heat is the fuel burned on the grate. All the reactions of combustion, whatever modifications are wrought by recuperation in order to retain the calories, or by the steam, carbon dioxide, etc., in order to enrich the gas, are always reduced to this single resultant: A liberation of calories equal to the number of calories set free by the fuel combining with cold oxygen, borrowed from the atmosphere.<sup>1</sup>

This heat of combustion, which is easily ascertained by consulting tables of the calorific power of chemical compounds or elements, or by experiment in the case of coals, etc., is then the invariable term of comparison for all exchanges of calories, for all heats—lost, recuperated or utilized in the furnace.

(2) Burned or oxidized gases, as water or carbon dioxide, can never furnish any calories. If by any reactions they are broken up in a portion of the furnace, in order to obtain either carbon monoxide, hydrogen or oxygen, this reaction absorbs heat and cools the gas and the furnace at that point. The later combination of the gases set free has only the effect to restore to another part of the furnace an equal quantity of heat, without the total heat liberated by the fuel and made available being in any way modified. In this case there is transport of heat from one point to another, without any gain in calories.

(3) The only gas supporting combustion in a furnace is the atmospheric air. If steam or carbon dioxide used in a furnace

<sup>1</sup> This is understood evidently of a self-contained gas-producer. If the necessary steam is vaporized in an independent boiler, or if the air necessary to the combustion is pre-heated in an independent furnace, there will be a further contribution of calories. If, on the contrary, the water is introduced as liquid in the ash-pit of the producer, and is liberated with the waste products in the atmosphere as steam, there will be from this fact an additional expenditure of calories for the vaporization, to be subtracted from the available heat.



is decomposed in one portion of the furnace, liberating oxygen, they recombine in another part without having given up any oxygen to the carbon or combustible gases from the fuel.

*Axiom: The total quantity of air necessary for the fuel combustion, escaping through the stack as water vapor, carbon dioxide and nitrogen, is always the same for a given weight of the burned fuel.*

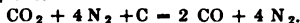
Two consequences of this principle have not been recognized by several inventors. The first one is that in the products of combustion the ratio of the volume of carbon dioxide to that of nitrogen is always the same for a given fuel, whatever the method of gasification, whether the producer is blown with air alone, air and steam, or air, steam and carbon dioxide from the waste products. People have erroneously sought to decrease this ratio by blowing steam into the producer. This course is wrong.<sup>1</sup>

The second fact not recognized is that the mass of the products of combustion sent through the stack cannot be decreased for a given weight of the fuel.

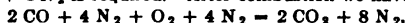
In the New Siemens furnace, in sending to the gas-producer part of the waste products, the idea may arise that some of the waste products with their calories have been diverted from the stack. This reasoning, which may give a wrong impression of the value of the New Siemens furnace, is also inaccurate.<sup>2</sup>

<sup>1</sup> The theoretical water gas  $\text{CO} + \text{H}_2$  does not carry, it is true, any nitrogen as the Siemens gas,  $\text{CO} + 2\text{N}_2$ , but the combustion of the two gases gives  $\text{CO}_2 + 4\text{N}_2 + \text{H}_2\text{O}$  and in the other  $\text{CO}_2 + 4\text{N}_2$ , and the waste products have in both cases the same ratio of  $\text{CO}_2$  to  $\text{N}_2$ , therefore the quantity of air going through the furnace is the same in both cases.

<sup>2</sup> We believe it useful to refute this error, in regard to the New Siemens furnace, by explaining the circulation of the various gas currents in that furnace. Upon leaving the hearth the waste products are effectively divided into two parts; let us suppose that the two parts are equal, which case is the most favorable to the system. This allows the gasification of the fuel without any primary air being required (see page 116). A mass of products of combustion expressed by the formula  $\text{CO}_2 + 4\text{N}_2$  goes to the stack, while an equal mass goes to the gas producer. Upon contact with the incandescent carbon the following reaction takes place:



In order to burn this gas, which has the same amount of nitrogen as the ordinary Siemens gas, a mass of air  $\text{O}_2 + 4\text{N}_2$  is required. After combustion we have



or a quantity exactly double that sent to the stack or to the producer, and also double that resulting from the combustion of the fuel with air. The mass of the products of combustion passing through the furnace is then double that of an ordinary Siemens furnace. It is possible to see that there are two gas currents—one acting as in the ordinary furnace, going from the producer to the stack; the other traveling in a closed circuit, from the producer to the hearth and from the hearth to the producer, without any modification in the heat-balance sheet, once the working is established (and without any very evident advantage).

(B) *Steam and other Auxiliaries in Gas-Producers.*—Since the use of steam does not modify the total available heat, nor the total necessary air for combustion, nor the proportion of nitrogen cir-

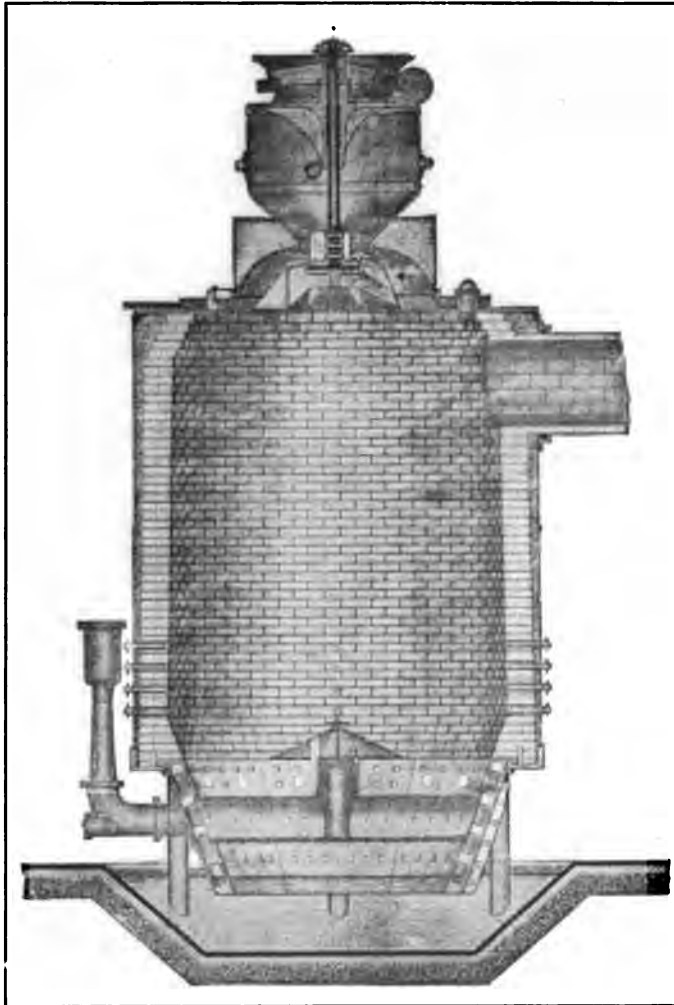


FIG. 18.—WATER-SEALED TAYLOR GAS-PRODUCER, WITH BUILD AUTOMATIC FEED.

culating through the hearth, the function fulfilled by steam, the usefulness of which is well established and approved by general practice, should be given with precision. It is closely related to recuperation.

In a producer blown with steam, the reactions giving rise to gas are the following:

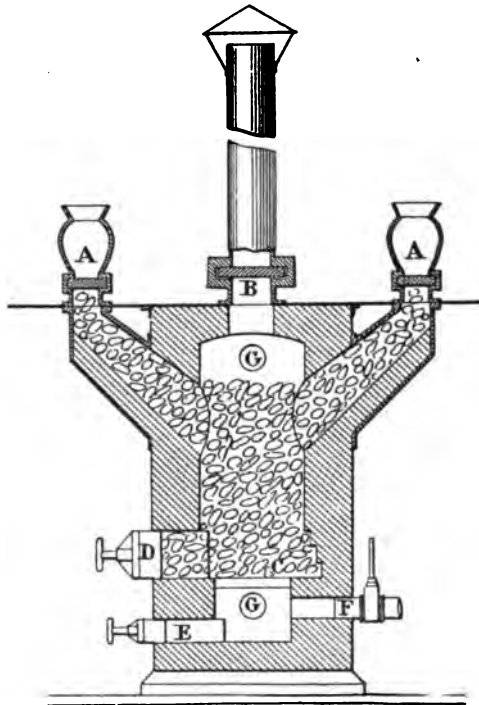
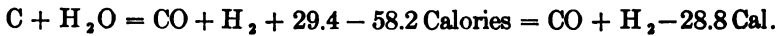
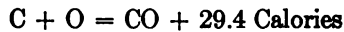


FIG. 19.—DELLWICK-FLEISHER WATER-GAS PRODUCER.

The first equation is exothermic, and tends to bring the producer to 1300° C.; the second is endothermic, and would tend to extinguish the producer if the steam were not regulated, so that the temperature is not brought below 600°, the lowest temperature

limit of the ignition of carbon. The first effect of steam is the lowering of the temperature of the gas in the producer. To this lowered sensible heat there corresponds an increased latent heat in the gas.

These results are of importance, but the resulting advantages vary greatly, according to the different cases. When the gas is burned in the hearth as it leaves the producer, the increase in

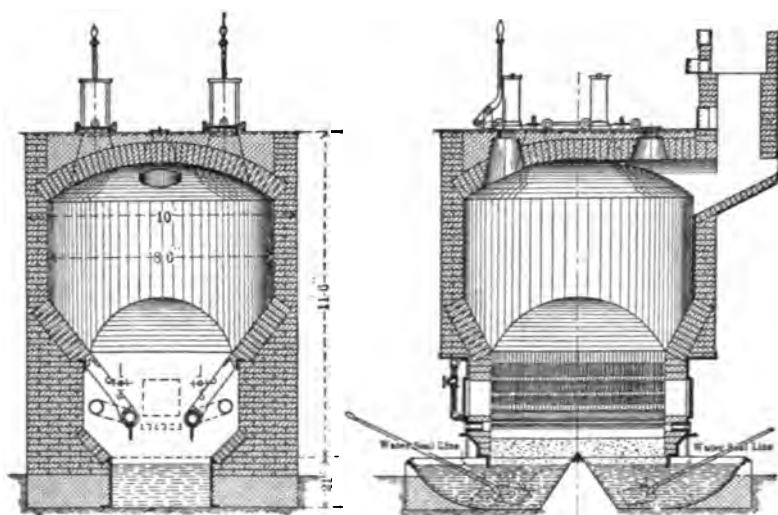


FIG. 20.—SWINDELL GAS-PRODUCER WITH DOUBLE FACE. VERTICAL SECTIONS ON LINES AT RIGHT ANGLES WITH EACH OTHER.

(From Ingalls' "Metallurgy of Zinc," p. 316.)

latent calories is purely fictitious, since in the hearth the latent heat and the sensible heat are equivalent.

On the contrary, when the gas is burned only after having suffered a change in its temperature, either becoming cool as in furnaces using cold gas, or becoming heated as is the case when the gas is recuperated, the increase in the latent heat is then very useful.

In furnaces provided with double recuperation the two effects

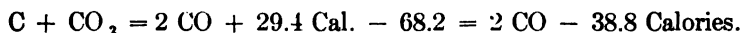
supplement each other. The lowering of the temperature allows better recuperation, and owing to the use made of calories, otherwise lost, the injection of steam gives a very real gain of calories, and therefore increases the efficiency.

A final result of the use of steam is the modification it brings in the ratio of the primary air to the secondary air. It is well known that, in gas-fired furnaces, the combustion of the fuel takes place in two steps, partly in the producer by the injection of air mixed with steam, and partly in the hearth by the admittance of the secondary air. In most furnaces the primary air is not recuperated, as the question of the preservation of the grate when using hot blast is yet unsolved; the secondary air, however, is always recuperated.

The decrease in the amount of the primary air has as a result a corresponding increase of the secondary air, and thereby allows a further saving of calories and in most instances affords a greater efficiency.

It will be seen, then, that steam acts as an auxiliary of recuperation. Doubtless in some instances it will react on the temperature of the hearth, but only in the same way as the recuperation itself, tending to raise the temperature of combustion. Its power to increase the latent calories in the gas is of importance only when the gas is used cold; this case, however, does not enter into our study.<sup>1</sup>

Other gases than steam can be used as auxiliaries of the fuel gasification. Thus carbon dioxide acts precisely in the same manner:



The breaking up of carbon dioxide in the producer absorbs heat and lowers the temperature of the gas; its use decreases the amount.

<sup>1</sup> When producer-gas or lean gas is used for explosion gas engines, the increase of the latent heat is the most beneficial: for such purpose the Buire-Lencauches producers blown with steam are much used. *Remark:* A further advantage of the use of steam, foreign to recuperation, is the help it gives in the operation of gas-producers, whenever the fuel used has a fusible ash. By lowering the temperature of the producer it not only prevents, to a large extent, the formation of clinkers, but also disintegrates the clinkers formed. The decrease in the amount of clinkers will result in a cleaner ash, the carbon contents being lower.—*Translator.*

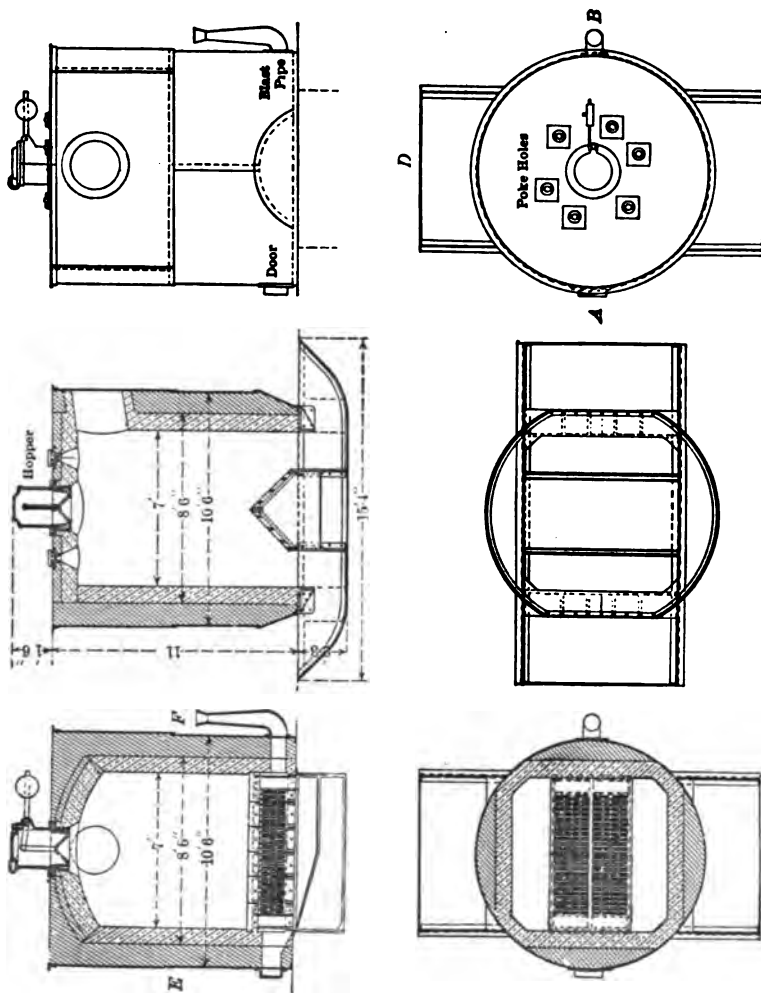


FIG. 21.—DUFF GAS-PRODUCER.

Cuts, from top, left: Section A B. Section C D. Elevation. Section E F.  
Top view of grate and brick bearers. Plan.

(From Ingalls' "Metallurgy of Zinc," p. 306.)



of the primary air and increases that of the secondary. If the carbon dioxide is borrowed from the waste products, it has been seen that the volume of the gases traveling through the hearth is doubled. If the carbon dioxide is borrowed from other sources, as inventors have proposed doing, it would act exactly as the steam, with the additional advantage of not possessing any latent heat of vaporization. It would be more efficient, theoretically speaking, if it could be obtained in the gaseous state without any cost.

Among other bodies acting in the gas-producer in the same manner as carbon dioxide and steam may be cited heavy oils, tars, asphaltum, and even the hydrocarbons of the coal. We find in this the partial explanation of the better efficiency of some coals when used in the producers. When these bodies are thrown into the producer, they are volatilized and highly heated at the expenditure of the sensible heat of the producer. Therefore, they cool the gas and prepare it for a good recuperation; and, further, their gasification does not acquire any primary air.

The use of tar in the producers of some steel works, in order to increase the efficiency of the recuperation and thereby the temperature of the hearth, is strictly in line with the above deduction.<sup>1</sup> It indicates also the advantage which would follow the use of petroleum, hydrocarbons, natural gas,<sup>2</sup> etc., in the Siemens furnace.

(C) *Fundamental Principles of Recuperation.*—The utilization of the calories carried away by the waste products as they leave the hearth at a high temperature necessitates the use of solid bodies, in order to avoid the mixing of the reacting gases. These solid bodies are either networks of refractory bricks, or ducts of metal or refractory materials. In the first case they accumulate the calories for a certain period of time, and during the succeeding period transfer them to the gases to be recuperated; in the second case they are permeable to heat to a greater or lesser degree, allowing

<sup>1</sup> Another contributing cause in this case is that the heavy hydrocarbons generated by the use of tar in the producer burn with a very luminous flame. It is well known that the luminosity of a flame has a very useful effect in the furnace hearth, by increasing the radiation.—*Translator.*

<sup>2</sup> Natural gas cannot be efficiently pre-heated on account of the heavy deposit of soot in the brick network, resulting from the breaking up of the hydrocarbons.—*Translator.*

the transfer of the calories from the hot gases to the cold ones (air or producer-gas). In both cases they act only as heat-carriers; therefore it is permissible, in a theoretical study, to consider only the reacting gas masses, one mass losing its calories, the other gaining them. Under such conditions, two self-evident laws govern this exchange. Both are derived from the fact that an exchange of calories can take place only from a hot body to a cooler one.

(1) In order that the total recuperation of the calories held in the products of combustion be possible, it is necessary that the gases that are to absorb the calories be at the temperature of the outside air into which the products of combustion are discharged. This condition is fulfilled only by the air, as the producer-gases are always at a higher temperature than the atmosphere. It follows that, in a furnace with double recuperation, secondary air and gas, the total recuperation is always impossible, because a part of the waste products cannot give up all the calories it holds.

(2) In order that the exchange of calories between two gaseous masses be perfect (that is, that after recuperation the final temperature of one mass be equal to the initial temperature of the other), it is necessary that the total thermal capacities of the masses present be equal between the temperatures under consideration. If the specific heats are unequal—or, what is more frequently the case, if the masses are unequal—the hot gas which is to give up its calories will escape at a temperature different from that of the gas to be pre-heated.

When the mass of the first gas is too large the recuperation will be incomplete, and the waste gases will escape at a temperature higher than the one of the atmosphere. Inversely, when the gas to be pre-heated is in excess, these gases will absorb all the calories, but their temperature will not reach the initial temperature of the waste products.

The first case—excess of waste products—is the one generally met with in furnaces. The thermal capacity of the air necessary for combustion is always lower than the thermal capacity of the products of combustion; therefore, even heating the total air

would not secure complete recuperation. The double recuperation by the air and the gas does not secure complete recuperation, since the thermal capacity of carbon monoxide is lower than that of carbon dioxide.

Triple recuperation—primary air, secondary air and gas—alone may give complete recovery of the calories of the products of combustion. On the point of masses the limit is reached and even exceeded, since the primary air is pre-heated twice; it passes once through the chambers before its injection into the producer, and it is subjected to a second recuperation with the producer-gas on its way to the hearth. In the second case, on account of the inequality of the masses, the air and the gas will leave the recuperators less hot than the products of combustion at their entrance through the same, however perfect the apparatus.

HYPOTHESES REQUIRED FOR THE MATHEMATICAL THEORY OF  
COMBUSTION IN THE RECUPERATIVE GAS-FIRED FURNACES;  
SELECTION OF THE METHOD USED FOR THE  
CALCULATION OF THE EFFICIENCY.

In order to eliminate some variables from our general equation of heat utilization and to reach the general theory of recuperation, it is necessary to assume certain hypotheses.

(1) We will admit in our calculations that the complete gasification of carbon into carbon monoxide, without any admixture of carbon dioxide, is possible.

This hypothesis does not conform with practice, since producer-gas always carries a certain percentage of carbon dioxide. Ledebur, in his treatise on metallurgy<sup>1</sup>, gives examples of gas analyses where the CO<sub>2</sub> is below 1%, which would justify our hypothesis; however, since such results are very rare, it will be necessary for us to discuss the influence of the premature combustion of the gas on the heat utilization.

(2) We will suppose that the exchange of calories is perfect between the two gas masses, the products of combustion giving up their calories, and the gas to be pre-heated absorbing them.

<sup>1</sup> "Genie Civil," Tome XXIX, No. 4, p. 59.

In other words, we will suppose that the temperature of the recuperated gas will be equal to the temperature of the products of combustion at the moment of their leaving the hearth.

This hypothesis is quite far from reality, since the rate of exchange of calories between a gas and a solid body in contact with it is greater the larger the gap between the irrespective temperatures; as the gap becomes small the rate of exchange becomes very small. Since recuperation necessitates a double transfer of calories between a solid and a gas, it is found in practice that the exchange from gas to gas is limited to a difference in temperature generally greater than  $300^{\circ}$ . Here, also, we will be obliged to discuss the influence of this disturbing factor, since we cannot include it in our calculations.

(3) We will admit that the furnace has an invariable ruling temperature in all its parts.

This condition is fulfilled in continuous furnaces using the parallel counter-current system of recuperation, but it is not exactly true of furnaces using inversion. Let us assume, then, that the chambers are large enough and the inversion frequent enough to maintain the constancy of temperature between two inversions. Our hypothesis will, therefore, conform closely to practical conditions. Hence it will not be necessary for us to discriminate between the two systems of recuperation; the results found will apply as well to the Siemens system as to the parallel counter-current system.

(4) The heat radiation from all organs of recuperation, chambers, flues, and gas producers is supposed to be small enough to be negligible.

This hypothesis is evidently inaccurate; radiation is essentially a function of the form and of the method of construction of the furnaces. It would be impossible to enter such variables in our calculations. The radiation of the hearth, however, is part of what we have defined as "utilized heat."

(5) We will suppose that our fuel is carbon, the equivalent of an ashless coke.

It results from all the above hypotheses that our gas will be formed of carbon monoxide, or carbon monoxide and hydrogen,

without admixture of carbon dioxide, water vapor or hydrocarbons; that the gas brings to the furnace the whole of its sensible heat; that the gases subjected to recuperation enter the hearth at its ruling temperature; and, finally, that the products of combustion enter the recuperators at that same temperature, arbitrarily selected. In other words, if the ruling temperature of a furnace with double recuperation is, say, 1500°, the secondary air and the gas enter the hearth at a temperature of 1500°. If the furnace has single recuperation, the air enters the hearth at 1500°, the gas enters at the temperature of combustion of the carbon burned to carbon monoxide in air, mixed or not mixed with steam, and the products of combustion escape from the hearth at 1500° and enter the chambers at the same temperature.

We may remark that these hypotheses favor the perfect utilization of the heat in the furnace. They mean simply that, from the point of view of the utilization of heat, the organs of recuperation have reached perfection. It is toward this perfection that all improvements tend. Our hypotheses are therefore legitimate. The theoretical calculations made by their use will give us, in an accurate manner, only the maximum heat utilization or the minimum losses in the furnaces. The results thus obtained are not only interesting but they may also serve as a sure guide in an experimental study of a given furnace, as they allow appreciation of its good and bad points.

However, from the point of view we have taken, the comparison and classification of the various systems of furnaces are not sufficient. Nothing warrants us to say, *a priori*, that the classification of the furnaces, based on their maximum efficiency, will still hold true when the furnaces are working under the conditions met in practice.

We will then have to review our various hypotheses in order to see what modifications in the absolute values of our figures will bring the practical conditions, and thus ascertain the change in the order of the classification. We will make use, therefore, of our hypotheses, with the reservation of a subsequent examination.

*Calculation of the Efficiency of a Furnace.*—In our general equation

$$Q = P + U$$

we will give to the terms  $P$  and  $U$  the specific meanings given them in our hypotheses:

$P$  = heat escaping recuperation, or heat escaping, with the waste products.

$U$  = Maximum of the heat utilized in the furnace.

And since  $Q$  is always known either by the direct measurement of the calorific power, or indirectly by means of the heats of combustion of chemical elements or compounds, it is possible to compute  $U$  or  $P$  and to obtain by difference  $P$  or  $U$ .

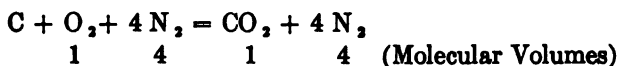
Of the two methods we have selected the direct calculation of  $P$ , with the idea that the knowledge of the heat lost is the essential point in a study of furnaces. Furthermore, the computation of  $P$  allows us to easily find the temperatures of the gases leaving the chamber, and to obtain an insight of what takes place in the recuperative apparatus.

The direct calculation of  $U$  has its special interest in the case of the study of the phenomena taking place in the hearth. Its calculation will be the object of a later study.

## CHAPTER IV.

### DIRECT-FIRED FURNACES—BOILERS.

*Characteristics of Direct-Fired Furnaces, and their Principal Industrial Applications.*—The combustion of the fuel in direct-fired furnaces takes place in one operation; the carbon is at once burned to carbon dioxide, the reaction being the following:



97.6 calories are liberated by the burning of one molecule (12 grams) of burned carbon.

In this case no attention need be paid to the steam sometimes injected under the grate, as is the case with boilers operated under forced draught with a steam injector. Sometimes, also, in furnaces operated for high temperatures, the workmen are accustomed either to wet their coal or to throw water on the grate, with the idea of bettering their fires. Whatever be the rationale of this practice, water is not broken into its constituents in a direct-fired furnace, and therefore does not take an active part in the combustion.

In order to better utilize the heat, the body to be heated is placed directly over the flame, and often in contact with it. All the waste products go to the stack, carrying away all the available calories not made use of in the furnace proper.

In order to have perfect combustion, it is necessary to have an excess of air. This excess is often considerable, as the air generally has free access to the grate, and can be regulated only as far as the fire can be regulated; nevertheless, it is seldom that the combustion is complete, as is indicated by black smoke, showing that abundant coal-dust and soot have been subtracted from the combustion.

With the above conditions—loss through smoke, excess of air and incomplete combustion—a low efficiency results. In spite of this, direct-fired furnaces are largely in use on account of their simplicity and the economy of their construction.

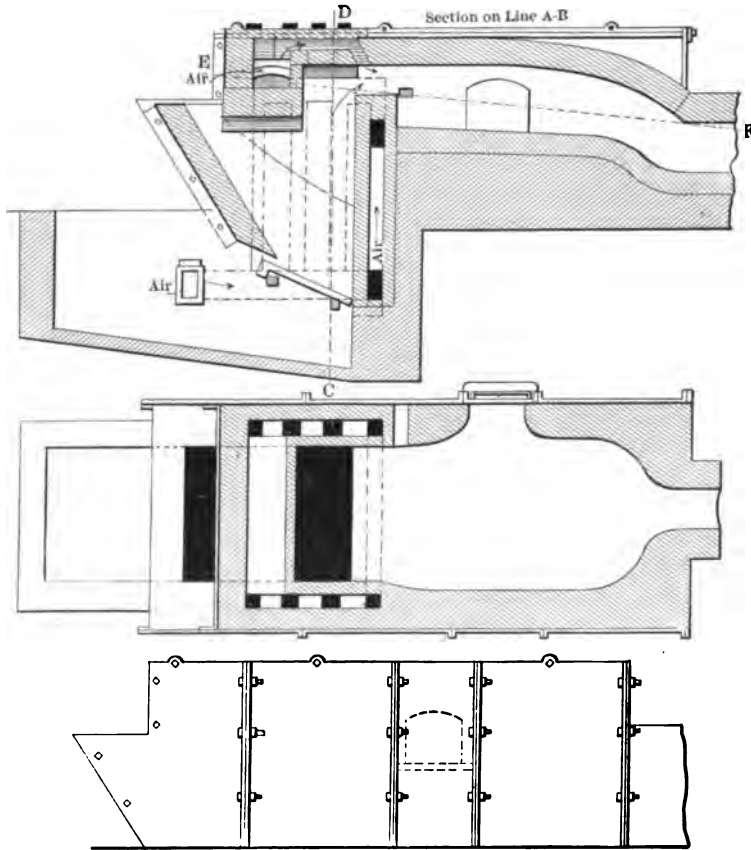


FIG. 22.—BOËTIUS FURNACE.

(From A. H. Sexton's "Fuels and Refractory Materials.")

The old glass-pot furnaces and most reverberatory furnaces for metals other than iron, kiln furnaces for porcelain and earthenware, muffle furnaces, annealing furnaces for glass and brass,



etc., are without recuperation. Certain furnaces with a deep fire-bed constituting a true producer, and where high temperatures are obtained by pre-heating the air, as the Bicheroux furnaces used in metallurgy, and the Boëtius furnaces in glassworks, are still furnaces with direct firing without recuperation. Their products of combustion are discharged directly into the atmosphere.

Puddling and re-heating furnaces are also direct-fired furnaces; in most instances, however, they are connected with steam boilers—excellent organs of recuperation. They are worthy of a special study. Boilers form by far the largest class of this group.

It should be said, however, that if all these furnaces are not provided with gas recuperators, they are not wholly without means for making use of some of the heat escaping the main hearth. Without mentioning furnaces followed by boilers, many reverberatory furnaces have several hearths of decreasing temperatures. The ceramic furnaces have a hearth where the first firing given the potteries is at a temperature lower than that of the main hearth, where the enameling is done.

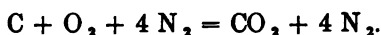
Through these devices the efficiency is often greatly improved. From this remark it follows that the ruling temperature of the first hearth is without any great importance to the heat utilization. The two items which, in direct-fired furnaces, allow the estimation of the value of a furnace, are the temperature and the chemical composition of the products of combustion at the stack.<sup>1</sup> From this data the heat lost can be computed, and by difference the utilized heat is found.

In our study of direct-fired furnaces we will calculate the heat losses for all temperatures and for the composition of waste products usually met in practice, assuming the fuel to be ashless coke.

*Heat lost, P, for all Temperatures, the Combustion Taking Place with the Theoretical Amount of Air.*—Let us take a weight of pure coke (carbon), say 12 grams, giving by its combustion a molecular volume of carbon dioxide, and liberating 97.6 calories. The necessary oxygen is accompanied by a volume of nitrogen  $\frac{79.2}{20.8}$

<sup>1</sup> Let us recall that in non-recuperative furnaces the stack begins at the hearth exit, and the temperature should be taken at that place.

which for the sake of simplicity we will call quadruple the volume of oxygen. We have seen that the equation of combustion is



The products of combustion will be composed of 4 molecular volumes of nitrogen and 1 volume of carbon dioxide. The calories carried away by these products are easily found by using the table of thermal capacities (Tables 6, 7). The calculations are shown in the following table:

CALCULATION OF LOST HEAT, P, IN DIRECT-FIRED FURNACES AT 300°, 1000°, 1500° C.

Reaction = $\text{C} + \text{O}_2 + 4 \text{N}_2 = \text{CO}_2 + 4 \text{N}_2$			
Composition of the Waste Products = $\text{CO}_2 + 4 \text{N}_2$			
Calories set free = $Q = 97.6$ .....	300° C.	1000° C.	1500° C.
Calories carried away by (by Molec. Vol. of $\text{CO}_2$ .....	3.1	12.2	21.1
the Waste Products... (by 4 Mol. Vol. of $\text{N}_2$ .....	8.4	29.7	46.4
Total = P .....	11.5	41.9	67.5
P + Q = Ratio of Heat Lost to total Available			
Heat, P + 97.6.....	11.8	43.0	69.5
Percentage of Utilized Heat U .....	88.2	57.0	30.5

The utilization at 0° is evidently perfect, the efficiency being 100%. This is practically the case in domestic furnaces, where the apparatus is so built as to send the products of combustion to the stack at a very low temperature.

The efficiency is *nil*, the heat being totally lost with the products of combustion at the temperature of combustion of carbon in cold air, which we know to be 2040°. We are able to plot the curve of the heat lost, P, by connecting the five points found. The equation of this parabola, deduced from the thermal capacities, is the following:

$$Q(P) = 5 \times 6.5 \frac{T - T_0}{1000} + [4 \times .6 + 3.7] \frac{T^2 - T_0^2}{1000^2}$$

The examination of this curve (Fig. 23) gives useful information on recuperation. We find the summit of the curve to be 2040°.

the limit of temperature at which direct-fired furnaces can be used; beyond that temperature the use of grate furnaces is evidently impossible, unless the air is first pre-heated by recuperation or by some other device, such as is used in the Bicheroux furnaces.

Keeping in mind that an excess of 5% oxygen in the products of combustion is difficult to prevent, and that it corresponds to an excess of 25% of air, the temperature of combustion is lowered to 1650° (see page 17). The study of the curve of heat utilization

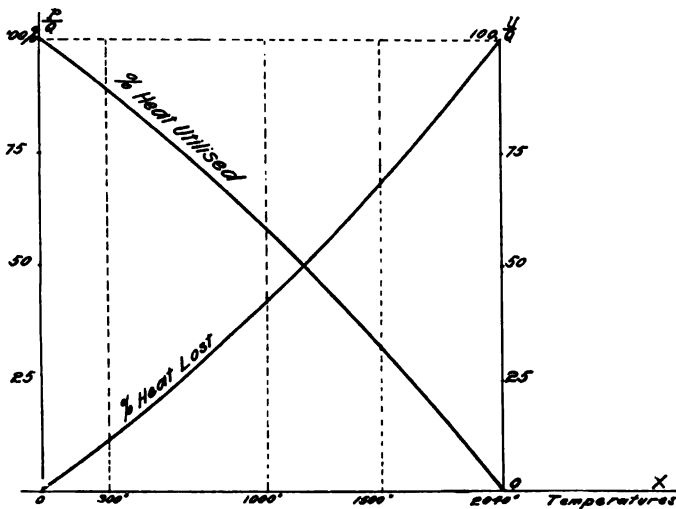


FIG. 23.—CURVES SHOWING THE PERCENTAGE OF THE HEAT UTILIZED AND LOST IN DIRECT-FIRED FURNACES.

shows that, for a heat efficiency of 10%, there should be a difference of about 150° between the temperature of the hearth and the temperature of combustion; it follows that 1500° is about the maximum temperature to be realized under industrial conditions when burning cold air, and then the efficiency is far from being satisfactory. The only furnaces in use under such conditions are blacksmith forges, where, with forced draught, heating is done by bringing the iron pieces into close contact with the fuel. Here radiation is reduced to a minimum, and the excess of fuel allows us

to always have perfect combustion in a portion of the firebed corresponding to  $2040^{\circ}$  C. The temperature of  $1500^{\circ}$  explains the necessity of recuperation for the metallurgy of steel. It may be added that, without recuperation, the melting of steel in open-hearth furnaces would not be possible, since the ruling temperature in these is  $1600^{\circ}$  and over.

In the glass industry, on the contrary, the ruling temperature is only  $1450^{\circ}$ , or even less; hence, direct-fired furnaces may still be used, and there are quite a number in operation at present. When recuperative-furnace builders guaranteed to the glass industry a saving of fuel of 60%, that guaranty was not excessive, since the maximum heat utilization at  $1450^{\circ}$  is only 30%.

If the ruling temperature is lowered to  $1200^{\circ}$ , the efficiency rises to 50%. At  $1000^{\circ}$  it becomes equal to 60%, and this relatively high efficiency explains why, in industries where use is made of this temperature, it is so difficult to effect a substitution of the recuperative furnaces for the direct-fired furnaces. The manufacture of coal gas in retort furnaces, metallurgical operations with the Bicheroux furnaces, glass-making with the Boëtius furnaces, and kiln-firing of porcelain and earthenware, are effected in the neighborhood of  $1000^{\circ}$ . There is still a possible economy of 40%. Many such furnaces have been provided with recuperators; there are, however, many places yet where the introduction of recuperative gas-fired furnaces might result in a marked economy.

Now that the problem of high temperatures has been satisfactorily solved, this class of furnaces presents today the most promising field to engineers and furnace builders. From  $500^{\circ}$  down the efficiency becomes good, and the benefits to be derived from the use of recuperators are doubtful. Without condemning the attempts made in this line, let us recall that the introduction of the Siemens system to boiler firing has not been successful. In this case, from  $500^{\circ}$  down, steam boilers are, in fact, the best agent for the utilization of the heat of the fuel.<sup>1</sup>

*Furnaces Followed by Steam Boilers. Calculation of the Lost Heat, P, in a Puddling Furnace.*—In the discussion of direct-fired

<sup>1</sup> This opinion has often been advanced, and Lencaux has maintained that the steam boiler is the best recuperator; our figures corroborate this opinion.

furnaces, puddling and re-heating furnaces have been purposely omitted. In these, direct firing is, and doubtless will be for a long time to come, the general rule. The large amount of motive power required by iron works has led users to place steam boilers in connection with puddling and re-heating furnaces, thereby reducing the waste of heat. These boilers generate steam in general for low-pressure condensing engines. It is possible to give the boilers the design and heating surface best suited to high efficiency.<sup>1</sup> Thus, there is a series of beneficial conditions particular to metallurgical furnaces followed by boilers which have a very good heat utilization. It is interesting to find their exact efficiency.

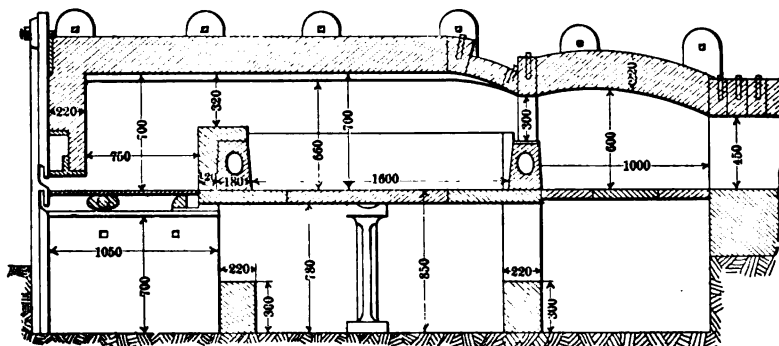
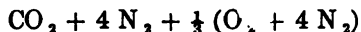


FIG. 24.—PUDDLING FURNACE OF THE FORGES D'EURVILLE. SECTION A B.

In Fig. 24 is shown an example of a puddling furnace with water-cooled hearth; it is followed by a boiler, not shown in the drawing. The boiler is horizontal, and gives a steam evaporation of 4 to 4.5 kg. of water per kg. of coal burned on the grate. The waste products have a temperature of 200 to 250° at the stack. Supposing, by analogy with similar puddling furnaces, that the combustion takes place with an excess of 5% oxygen in the waste products, corresponding to the formula



<sup>1</sup>However, they usually cannot be crowded, as their heating depends entirely on the ruddling furnace, and it may happen that, at the time when most steam is required, the boilers furnish the least.—*Translator*.

with a temperature of  $200^{\circ}$  at the stack, we find that only 9.8 calories out of 97.6 have been lost, corresponding to an efficiency of 90%—an efficiency higher than that of most systems of recuperation.

Therefore, there is little incentive, from the point of view of fuel economy, to substitute recuperative furnaces for the above type of puddling furnaces.

*Steam Boilers. Heat Lost When Combustion is Effected by the Use of a Large Excess of Air.*—The most interesting case to take up is that of the multitubular boiler used in marine engineering. There, fuel economy is most highly valued, and there, also, are met

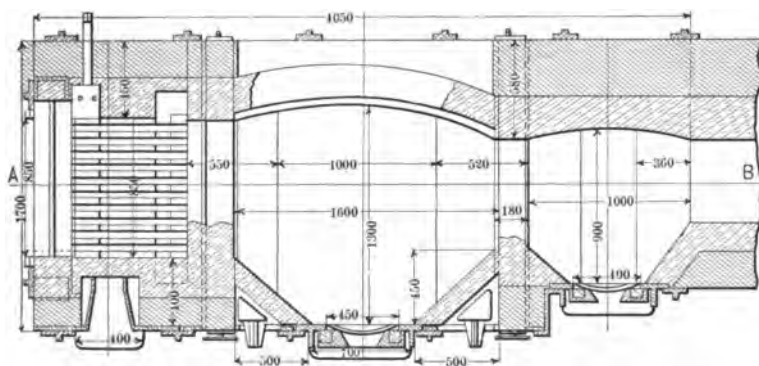


FIG. 24a.—PUDDLING FURNACE OF THE FORGES D'EURVILLE. SECTION C D.

the most unfavorable conditions (small volume and the necessity of quick steaming). This problem has also been the most thoroughly studied. Experimental data have been given us by the builders of the best known of this class of boilers. We give as examples the drawings (Fig. 25, 26 and Fig. 27, 28) of two types of marine boilers—the Belleville and the Niclausse. Both are multitubular, but the water circulation is different.

In the Belleville the tubes are placed in series; in the Niclausse they are in multiple on vertical collectors, and the circulation is established variously, according to the rate of steaming at which the boiler is operated. Such are the main differences between the

two systems. In both boilers and, in general, in all boilers with intensive vaporization, the difficulty encountered is the keeping

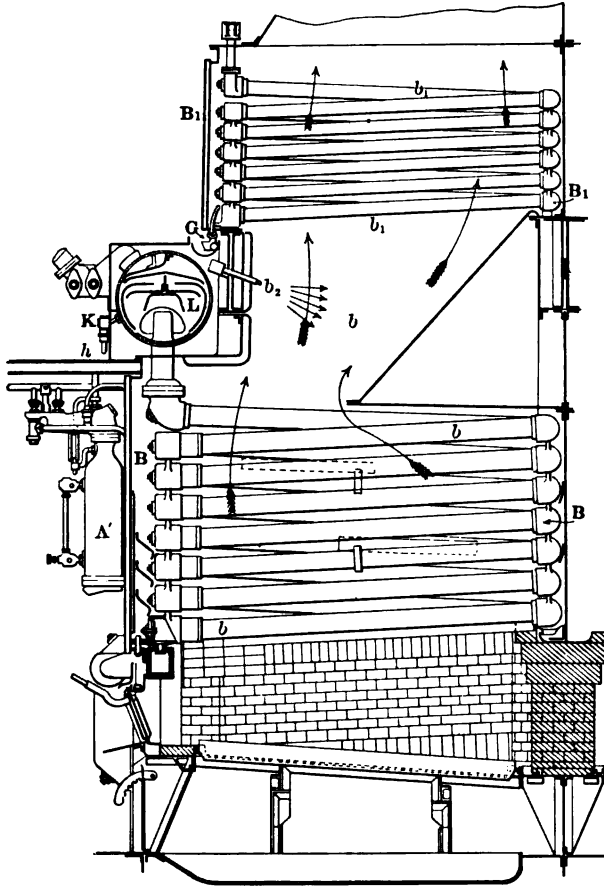


FIG. 25.—SECTION THROUGH A BELLEVILLE BOILER AND ECONOMIZER

of a low temperature in the waste products when the rate of combustion is increased.

The economizer introduced by M. Belleville is designed to re-

cuperate some of the heat, otherwise lost, by heating the feed-water and thereby bettering the fuel efficiency.

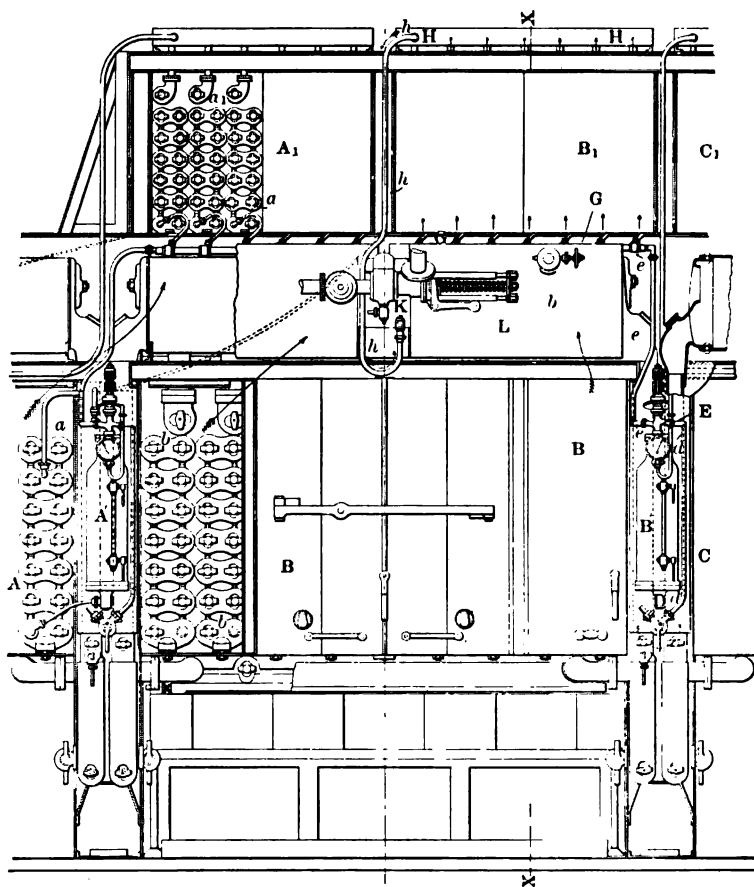


FIG. 26.—LONGITUDINAL SECTION AND FRONT ELEVATION OF A BELLEVILLE BOILER AND ECONOMIZER.

The Niclausse boiler has no economizer, but its system of circulation is such that the tubes furthest from the grate act as feed-water heaters.



The distinguishing feature of boilers, as compared with furnaces, is the lack of a ruling temperature. The temperature varies in a decreasing manner continuously from the grate to the stack.

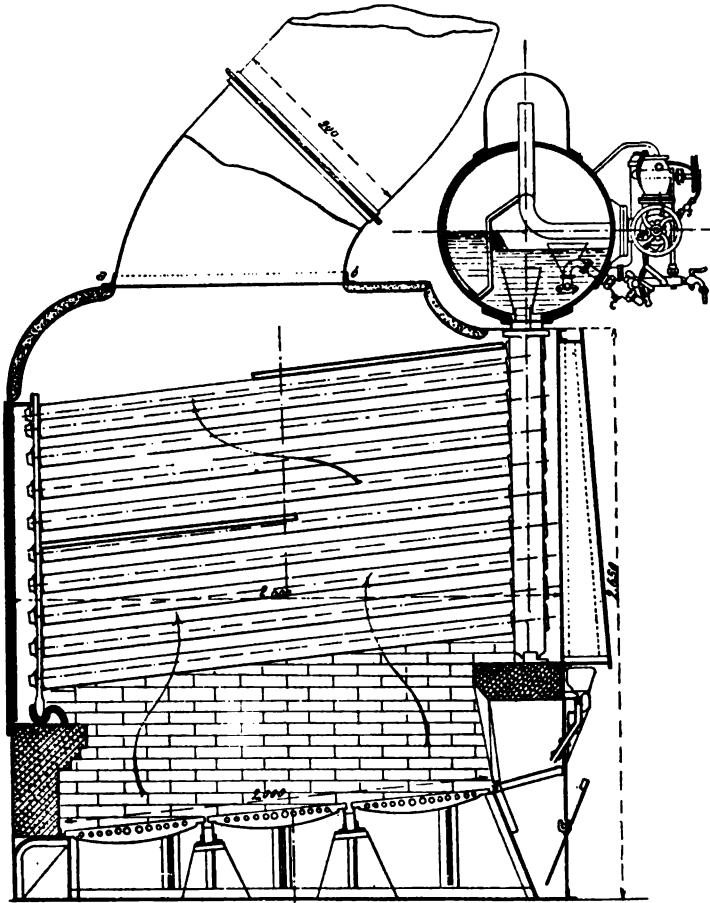


FIG. 27.—SECTION ALONG A B OF THE NICLAUSSE MULTITUBULAR BOILER.

In a theoretical study it is not even permissible to take as a ruling temperature the temperature of water vaporization at the steam-working pressure, since the extreme tubes in the Niclausse and

the economizer in the Belleville have a lower temperature. The only data allowing the calculation of the lost heat are experimental

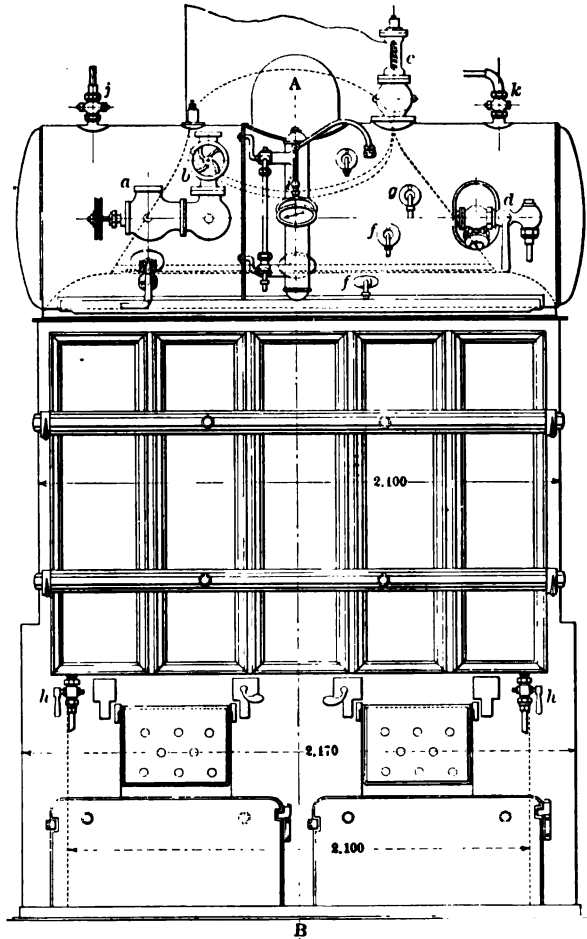


FIG. 28.—FRONT ELEVATION OF A NICLAUSSE MULTITUBULAR BOILER.

—the temperature of the products of combustion at the stack and the analysis of the gases.

The following data have been given us by M. Niclausse from a series of trials made of boilers built for torpedo boats. The temperature at the smoke-box varies widely, according to the rate of combustion. It is as low as  $140^{\circ}$  for a vaporization of 20 kg. per square meter of heating surface, and for a consumption of 100 kg. per square meter of grate-hour. It reaches as high as  $370-400^{\circ}$  for a vaporization of 55 kg. and a consumption of 400 kg. of coal.

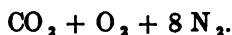
The Belleville boilers fitted with economizers have a temperature in the smoke-box varying from  $175^{\circ}$  for a coal consumption of 70 kg. per square meter of grate area to  $375^{\circ}$  for a consumption of 170 kg. of coal. The composition of the gases—the average of three tests on Niclausse boilers—is the following:

CO <sub>2</sub>	O <sub>2</sub>	CO	N <sub>2</sub>
8.2	10.	.80	81.

It is seen that it corresponds to a large excess of air: 10% of free oxygen corresponds to an excess of 50% of air. The water vapor present was not given.

To estimate the heat utilization in these boilers, we must make the calculation of P within the limits of the temperatures  $100^{\circ}$  and  $500^{\circ}$ , with the supposition that the excess of air in the waste products is equal to the volume of the products of combustion.

With this hypothesis the composition of the waste products is



We have 97.6 calories liberated per molecular weight (12 grams) of burned carbon.

Thermal capacities of the waste products:

Gas	200°	400°	600°
CO <sub>2</sub> .....	1.8	4.8	6.4
O <sub>2</sub> +8 N <sub>2</sub> .....	12.6	25.4	38.8
Total.....	14.4	30.2	45.2
% of loss.....	14.4	31.0	46.3

The curve of the heat utilization is traced from this data (Fig. 14). It is seen that, as soon as the boilers are crowded, the efficiency falls rapidly. For a temperature of 500° in the smoke-box—a temperature that may be reached at times—the utilization of the heat is only 65%.

It is, then, permissible to remark that there is a field for improvement in steam-boiler practice. The methods of gas recuperation have small efficiency at 500°. The recuperation by the heating of the feed-water has also a limit, and it would appear

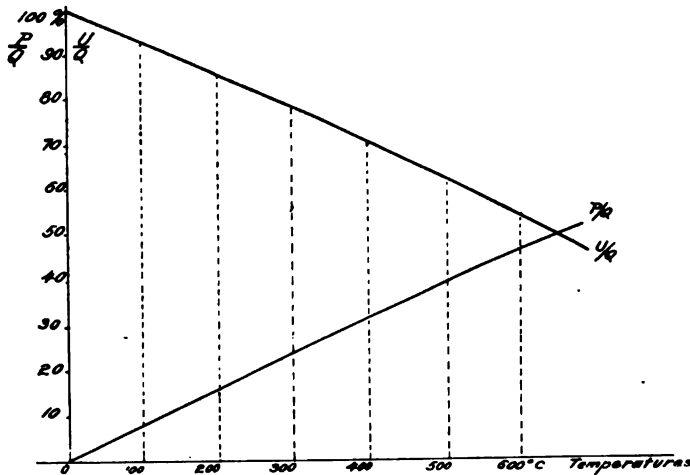


FIG. 29.—CURVES SHOWING THE PERCENTAGE OF THE HEAT LOST AND UTILIZED IN MULTITUBULAR BOILERS.

that the economizers have already given all that may be expected from them. The only remedy seems to be in the direction of perfect combustion without excess of air. The solution of the problem is, however, far from having the simplicity that might at first appear.

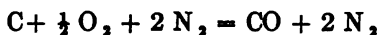
The use of gaseous fuel, which at high temperatures allows a closely neutral combustion, would probably be of poor efficiency in boilers, since the rate of combustion of gases is slower the lower the temperature. The combustion would most likely be incomplete,

and sooty deposition would take place. The very hot flame resulting from combustion without excess of air would injure the boiler shell, and other obstacles might be encountered. It remains true, however, that it is in the line of complete combustion, without excess of air, that the most gain is to be expected.

## CHAPTER V.

### FIRST CLASS OF GAS-FIRED FURNACES—SIEMENS GAS-RECU- PERATIVE FURNACES, FIRED WITH CARBON MONOXIDE.

The following reaction takes place in the gas producer:

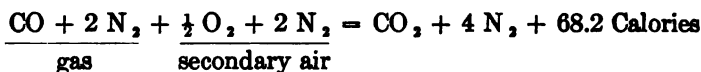


primary air

$\frac{1}{2} \quad 2 \quad 1 \quad 2$  Molecular Volumes,

with a liberation of 29.4 calories. The primary air being introduced cold, the temperature of the gas issuing from the producer is 1290°. If the primary air has been pre-heated, to the heat of combustion should be added the sensible heat brought from the producer. The temperatures of combustion are given in Fig. 34 for the temperatures 0°, 600°, 800°, 1000°, 1500° C.

The combustion is completed in the hearth according to the reaction:



The total liberated heat—29.4 + 68.2—is 97.6 calories, and the composition of the waste products is the same as in the case of direct-fired furnaces —  $CO_2 + 4 N_2$ .

*First Case. Recuperation by Means of the Secondary Air Alone.*—The furnaces coming under this heading are the retort gas-furnaces of the Compagnie Parisienne du Gaz, Siemens system, or Lencauchez system, where the draught is secured through natural means without the injection of any steam in the ash-pit; also, some glass furnaces provided with counter-current recuperation, as the Radot furnaces, Gobbé system large glass tank furnaces with Siemens recuperators, etc

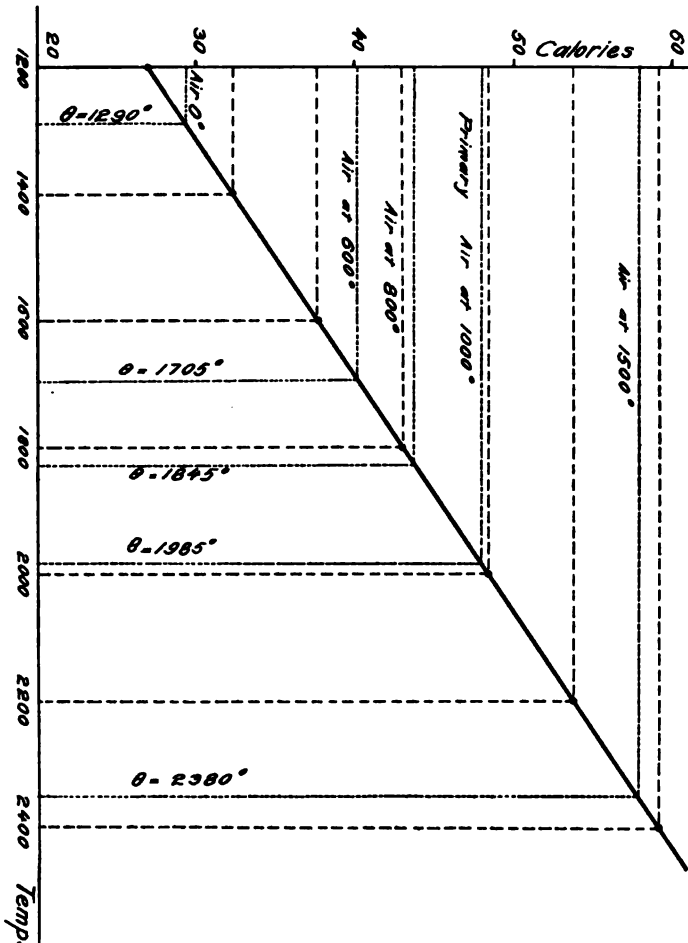


FIG. 30.—CURVE SHOWING THEORETICAL TEMPERATURE OF FORMATION OF SIEMENS GAS, THE PRIMARY AIR BEING INJECTED AT 0°, 600°, 800°, 1000°, 1500° C.

It is apparent that, notwithstanding the large use of mixed gas the number of furnaces of this type is still large.

We give two examples of these furnaces. Fig. 31, 32, from drawings furnished by the Compagnie Parisienne du Gaz, rep-





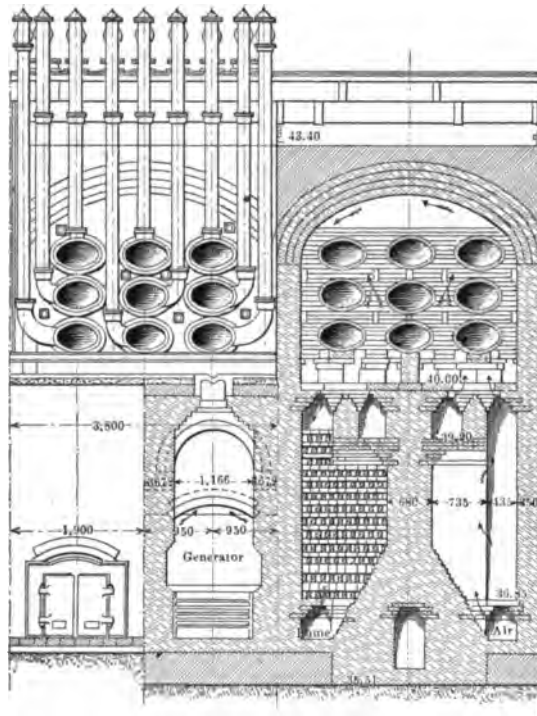


FIG. 32.—ILLUMINATING-GAS MUFFLE FURNACE OF THE COMPAGNIE PARISIENNE DU GAZ. SECTION E F, G H

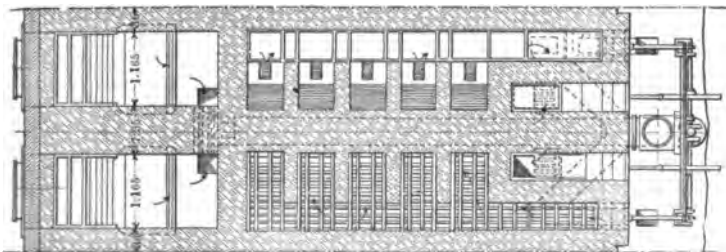


FIG. 32a.—SECTION L J.

resent its most approved type of Siemens furnace for gas retorts. From a practical point of view its construction is very interesting, for by the happy grouping of the recuperators the radiation of the chambers is reduced to a minimum. From the point of view of theory it comes very close to our hypothesis, since that furnace is fired with gas coke. The ruling temperature is about  $1000^{\circ}$ .

Fig. 33, from drawings given by M. Lencauchez, illustrates a furnace with only secondary air recuperation, the recuperators being of the parallel counter-current type, Lencauchez system. Its ruling temperature is higher than  $1400^{\circ}$ . This recuperator, as is well known, is formed by hollow firebricks.

CALCULATION OF THE LOST AND UTILIZED CALORIES IN FURNACES FIRED WITH SIEMENS GAS, WITH SINGLE RECUPERATION BY THE SECONDARY AIR.

Available (Calories = 97.6.....	1000°	1500°
Thermal Capacities of the Combustion Products..... $\left\{ \begin{array}{l} \text{CO}_2 \\ 4 \text{ N}_2 \end{array} \right.$	12.2 29.7	21.1 46.4
F - Total.....	41.9	67.5
Calories Recuperated by the Secondary Air..... $\left\{ \begin{array}{l} \frac{1}{2} \text{O}_2 \\ 2 \text{ N}_2 \end{array} \right.$	3.7 14.9	5.8 23.2
R - Total.....	18.6	29.0
Lost Calories = F - R.....	23.3	38.5
% of Lost Calories = P.....	24.0	39.5
% of Utilised Calories, Efficiency = U.....	76.0	60.5

The calculations for the heat efficiencies are given above.

As was the case with direct firing, the efficiency increases with the lowering of the ruling temperature, but at a much lower rate. There are no upper limits to the temperature to be attained.

If we have the secondary air pre-heated to  $1000^{\circ}$ , the gas being at its theoretical temperature  $1290^{\circ}$ , we find by the graphic method (Fig. 34) a temperature of combustion of  $3000^{\circ}$ .

We may, therefore, conclude that furnaces with single recuperation, fired with Siemens gas, can give all the usual industrial temperatures, and that within these temperatures the efficiency should always be 50%. For lower temperatures, and especially for the distillation of gas from coal, the efficiency reaches 75%.

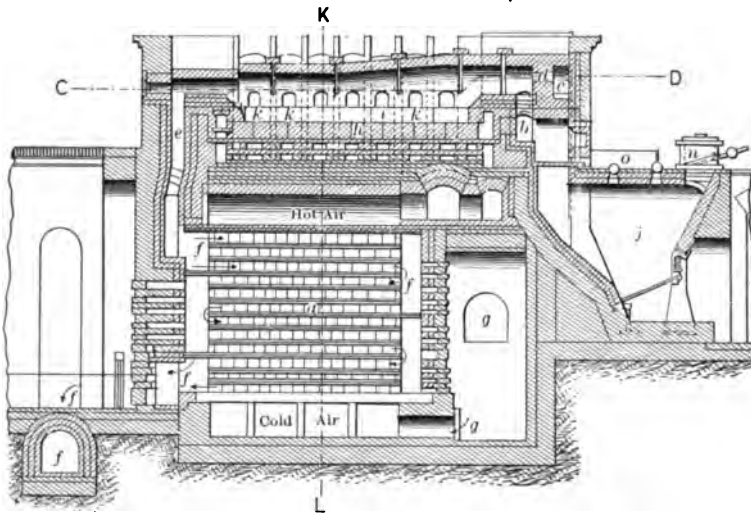


FIG. 33.—GLASS TANK FURNACE, FIRED WITH SIEMENS GAS, WITH RECUPERATORS OF THE LENCAUCHEZ PARALLEL COUNTER-CURRENT TYPE. [SECTION ALONG G H.]

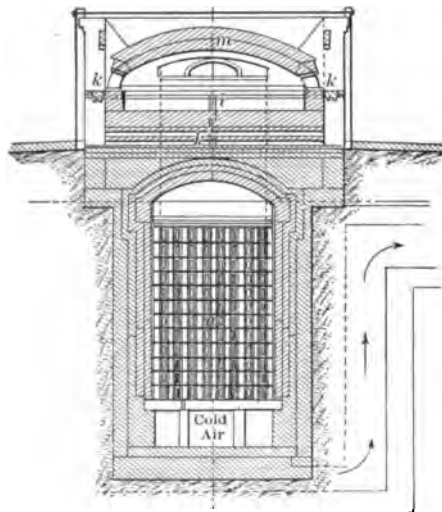


FIG. 33a.—SECTION ALONG K L.

This efficiency explains why the Compagnie Parisienne du Gaz has kept in operation a system of furnaces in which the recuperation is not perfect, but where the further gain of calories to be attained would not justify the cost and complexity of furnaces with four recuperative chambers fired with mixed gas. Therefore, we reach *a priori*, by theory, results that have been found in practice.

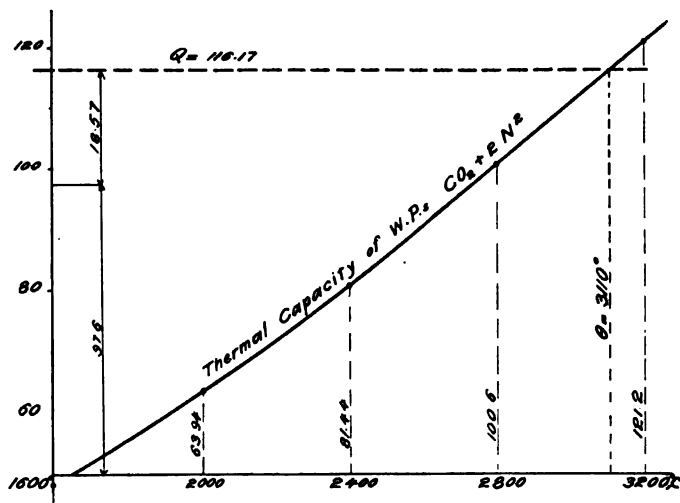


FIG. 34.—GRAPHIC DETERMINATION OF THE TEMPERATURE OF COMBUSTION OF SIEMENS GAS ( $\text{CO} + 2\text{N}_2$ ) HEATED TO  $1290^\circ\text{C}$ ., THE SECONDARY AIR BEING PRE-HEATED TO  $1000^\circ$ .

*Second Case. Furnaces with Double Recuperation for the Secondary Air and Gas.*—All the first Siemens furnaces, and especially the first Martin-Siemens furnaces, come under this heading. They were generally constructed with the inverted siphon; its function has been explained. This organ has been condemned, since it has become possible to build furnaces without it.

This much debated question will be discussed and our calculations will give its true value. It is one of practical interest, since there are furnaces of this type in existence.

In order to establish the heat balance-sheet of a furnace with double recuperation, it is necessary to add to the calories absorbed by the secondary air those absorbed by the gas. The gas is not cold, as it leaves the producer (according to our hypotheses) at the temperature of combustion of carbon burning to carbon monoxide in cold air—that is, 1290°. Therefore, for any ruling temperature below 1290°, gas recuperation is impossible, furnaces with four recuperative chambers are unnecessary, and the theoretical efficiency of such furnaces would be equal to that of a furnace with simple recuperation. We have to make our calculations only for 1500°.

**CALCULATION OF THE LOST AND UTILIZED HEAT IN A FURNACE FIRED WITH SIEMENS  
GAS, WITH DOUBLE RECUPERATION, SECONDARY AIR, GAS.**

Available Calories - 97.6 .....	1500°
F-Thermal Capacities of the Products of Combustion .....	67.5
R-Calories Recuperated..... { by the Secondary Air from 0° to 1500° ..	29.0
{ by the Gas from 1280° to 1500° .....	4.7
Total.....	33.7
F-R-Lost Calories.....	33.8
% of Lost Calories=P.....	34.6
% of Utilized Calories=U.....	65.4

**Remark.**—The calculation at 1000° is impossible; the double recuperation at that temperature would give the same result as the single recuperation.

The lost heat,  $P$ , is 34.6%, thus giving a bettering of efficiency of 4.9% over that of furnaces with single recuperation. Still a third of the available calories is swept away to the atmosphere by the products of combustion—more than enough to pre-heat the gas to 1290° (29.4 calories). Thus, with good recuperation it is possible to pre-heat the gas if it has been cooled by the siphon or by a long flue before entering the recuperator. In the case of Siemens gas there is, therefore, no waste of calories through the use of the siphon. It follows that it is perfectly rational to place the producer at any convenient location, since such design is not

wasteful either for proper efficiency or for the production of high temperatures.

The Siemens siphon and very long flues evidently have their drawbacks, since they cause deposition of tar and soot and thereby impoverish the gas. They should not be condemned on account of the radiation of the sensible heat of the gas, which would be wasted in case gas is recuperated. In that respect they are very rational. They have rendered good service in the beginning of the art, and may still be useful when it is not desirable to use mixed gas and when natural draught is a necessity.

As an example of a furnace with double recuperation using air and Siemens gas, there exists a glass furnace, Göbbe system, built in Russia, using wood for fuel. The gas, as it leaves the producer, encounters a water spray in order to condense any steam produced in the wood distillation. The gas enters the recuperator cold. We have here an extreme case in which gas recuperation is necessary.

*Third Case. Double Recuperation: Primary and Secondary Air.*—The complete recuperation of the total air is impossible under present industrial conditions. The ruling temperature of a producer blown with primary air, heated to the temperature of the hearth, would be so high that no known type of producer could be used; we have seen that it would be over 2000°. If the Ebelmen producer (Fig. 16), with ash fusion, could stand such a temperature the exterior radiation would be very high, thus compensating to a great extent for the advantage resulting from the pre-heating of the primary air.

The question of the preservation of the grate prevents any application of the system. It is difficult to reach a temperature of 500° in the ash-pit without burning the grates, so that this temperature is almost the limit of the heating of the primary air, and its application is even then very limited.

With the exception of the Klönne furnace at Dartmund, fired with mixed gas, and of trials with pre-heated air with Taylor, Lencauchez and Siemens producers, there is only the new Siemens furnace that realizes a partial recuperation of the primary air. The design of that furnace is well suited to it. It is only necessary to

operate it in a way the reverse of that employed by Biedermann and Harvey (in placing the ash-pit in communication with the air-chamber and not with the waste-product chambers) to have a simple pre-heating of the primary air. If necessary, the pre-heated air should be diluted with cold air, in order to lower its temperature below 500°.

Some of the new Siemens furnaces are today operated in this manner; the greater part, however, inject some products of combustion, steam, hot and cold air under the ash-pit. In any case, it is necessary to study the double recuperation by the total air in order to appreciate its value.

The calculation is very simple; the primary air being equal to the secondary air, it is sufficient, in the case of single recuperation, to double the figure of the recuperated heat. The results are given below.

CALCULATION OF THE LOST AND UTILIZED CALORIES IN FURNACES FIRED WITH SIEMENS GAS, WITH DOUBLE RECUPERATION BY THE TOTAL AIR.

Available Calories - 97.6.....	1000°	1500°
F - Thermal Capacities of the Combustion Products.....	41.9	67.5
R - Calories recuperated by the total Air.....	37.1	58.0
F - R - Lost Calories.....	4.8	9.5
% of Lost Calories - P.....	5.0	9.7
% of Utilized Calories, Efficiency - U.....	95.0	90.3

These results show the very high value of double recuperation by the total air. At 1500° there is still a loss of 10%, but at 1000° the efficiency may be considered as perfect, since the 6% left is required to secure the proper draught in the stack.<sup>1</sup>

Theory gives us, then, the direction in which progress is to be sought. It lies with medium recuperative furnaces, in which recuperation is today far from giving the fuel efficiency that might be attained.

<sup>1</sup> The case of the triple recuperation with primary, secondary air and gas is impossible with Siemens gas, since the temperature of the gas generated in a producer blown with recuperated air is too high to allow any recuperation.

The advantages of high-temperature producers were foreseen by Ebelmen, who advocated a grateless producer much like a cupola furnace. This idea, after having been a long time dormant, has been recently revived, and the Saillers producer illustrated in Ledebur<sup>1</sup> is practically an Ebelmen producer. The displacement of steam injectors by positive-pressure blowers in gas-producer practice gives a new lease of life to the problem of Siemens gas, and forms in a way a step towards the solution of the problem of hot-blast producers.

It must further be remembered that Ledebur showed that the increase of temperature in the producer tends to decrease the premature combustion of the gas. It is easy to conclude that the questions of recuperation by the primary air and the introduction of hot-blast producers are vital.

<sup>1</sup> Ledebur: "Manuel theorique et pratique de la Metallurgie du Fer." Paris. Baudry et Cie.



## CHAPTER VI.

### SECOND GROUP OF GAS-FIRED FURNACES—MIXED GAS.

*Reactions of Combustion.*—The continuous production of water gas is impossible without the use of an external source of heat in connection with the gas-producer. The reactions of gasification and of combustion in a furnace fired with mixed gas are as follows:

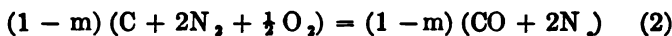
We burn our carbon unit, the molecule (12 grams), and a fraction "m" of the fuel is gasified by steam:



with the absorption of

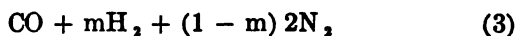
$$(29.4 - 58.2)m = -28.8m \text{ calories.}$$

The remainder of the fuel is burned by air.

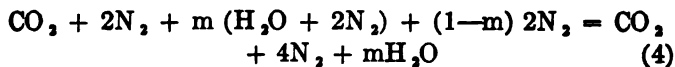


with the liberation of  $(1-m) 29.4$  calories.

The mixture of the two gases has for its composition



The combustion of this gas with the secondary air will give rise to products of combustion of the following composition:



The factor "m" controlling the reactions (1) and (2) is arbitrary between limits, and is a function only of the quantity of steam injected under the grate. The temperature of the generated gas varies inversely as the factor "m" is smaller or larger. This temperature must not be allowed to fall below a certain limit, otherwise the producer will be extinguished.

Experience has shown that below  $600^{\circ}$  the combustion of carbon in air ceases. It follows that the temperature of the gas will always be between  $600^{\circ}$  and  $1290^{\circ}$ , the temperature of gasification with dry air. As the amount of steam varies, the temperature of the gas also varies. In practice, when it is advantageous to produce mixed gas, the policy to follow is one of maximum production, with, therefore, the gas near  $600^{\circ}$ . This is the temperature limit used in our calculation. It is possible to find the numerical value of the factor "m," and therefore the chemical composition of the gases.

Let us suppose that the primary air is injected cold. To solve the problem it will be sufficient to know that the calories liberated by the combustion of  $(1 - m)$  grams of carbon in air, less the calories absorbed by the dissociation of "m" grams of water, will be in such amount as to bring the temperature of the gas to  $600^{\circ}$ .

$$-28.8m + 29.4(1-m) \geq \underset{0}{C}^{\underset{0}{600}} \left\{ m(\text{CO} + \text{H}_2) + (1-m)(\text{CO} + 4\text{N}_2) \right\}$$

We find that for  $m = \frac{1}{3}$  this condition is more than fulfilled, so that for a gas formed of  $\frac{1}{3}$  water gas and  $\frac{2}{3}$  air gas its temperature will be a trifle over  $600^{\circ}$ , and the producer will work satisfactorily.

This theoretical result is in accordance with the established practice of blowing the producer with a quantity of steam corresponding to a gasification of about one-third of the fuel.

If the primary air is pre-heated, the latent heat of the air is added to the 29.4 calories liberated by the partial carbon combustion, and the value of "m" increases. At the temperatures of  $1000^{\circ}$  and  $1500^{\circ}$  the pre-heating of the primary air would allow respectively 48 and 54%<sup>1</sup> of the fuel to be gasified, providing the temperature of the producer is maintained at  $600^{\circ}$ . In the same

<sup>1</sup> Results have been obtained as follows:

$$\begin{aligned} 29.4 - 58.2m + (1-m) \underset{0}{C}^{\underset{0}{1000}} \left( \frac{1}{2} \text{O}_2 + 2\text{N}_2 \right) &= \underset{0}{C}^{\underset{0}{600}} [\text{CO} + m\text{H}_2 + (1-m) 2\text{N}_2] \\ 29.4 + 18.2 - m(58.2 + 18.2) &= 12.6 - 4.2m \\ m &= \frac{35}{72.2} = .48 \end{aligned}$$

manner, if the steam were superheated, "m" would increase in value.<sup>1</sup>

*First Case. Recuperation by the Secondary Air.*—This case occurs in the furnaces of the Compagnie Parisienne du Gaz (Fig. 31, 32), when they are operated with water in the ash-pit and by natural draught, or with closed ash-pit and injection of air by

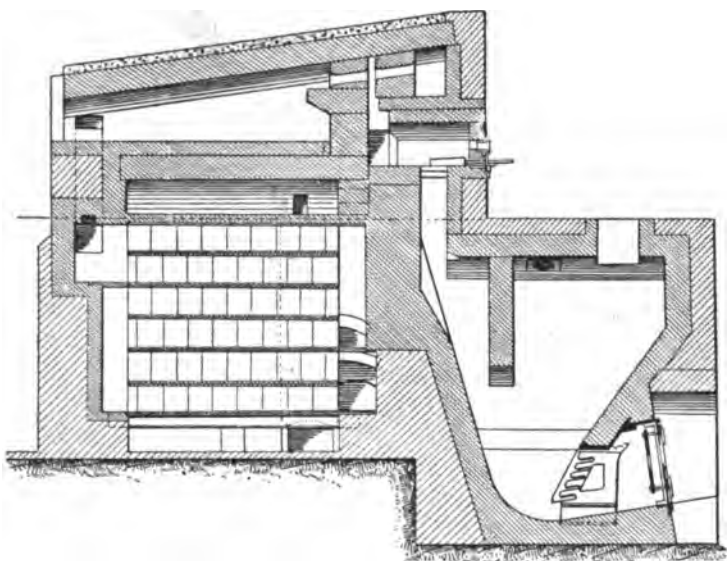


FIG. 35.—LENCAUCHEZ BRASS FURNACE, FIRED WITH MIXED GAS, WITH SIMPLE RECUPERATION OF THE PARALLEL COUNTER-CURRENT SYSTEM.

means of a Koerting steam injector. The Siemens glass tank furnaces and the Götting and Radot-Lencauchez furnaces are also operated with mixed gas, as well as many furnaces in use in the metallurgy of copper, as those of the Société des Métaux.

We give as an example (Fig. 35) a furnace for brass melting, with simple recuperation. It is of the Lencauchez parallel counter-current system. The producers of this furnace generate a gas

<sup>1</sup> Throughout the discussion of the cases arising from the use of mixed gas, we presuppose that the water is introduced in the form of steam; that is, we neglect the latent heat of vaporization—10.8 calories per molecular volume of steam.



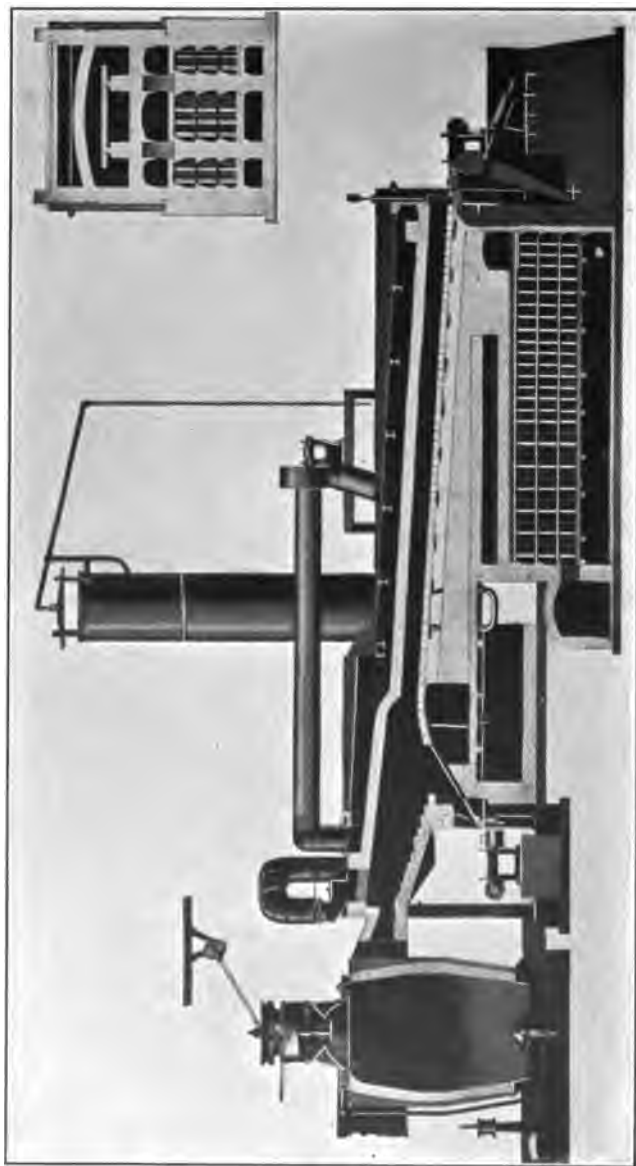


FIG. 36. —MORGAN GRAVITY-DISCHARGE BILLET-HEATING FURNACE.

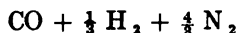
containing 12% of hydrogen. The ruling temperature is slightly below 1000°.

Let us calculate the heat utilization, giving to "m" the value  $\frac{1}{3}$ :

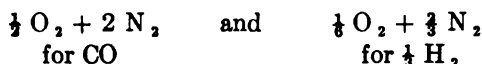
$$\frac{1}{3} (C + H_2O) = \frac{1}{3} (CO + H_2)$$

$$\frac{2}{3} (C + \frac{1}{2} O_2 + 2 N_2) = \frac{2}{3} (CO + 2 N_2)$$

The composition of the gas is



The required quantity of secondary air is



It is to be noticed that this quantity is greater by one-third than for the Siemens gas. The composition of the waste products is  $CO_2 + 4N_2 + \frac{1}{3} H_2O$ , and the thermal capacities of these waste products is also greater than that of the Siemens gas by the entire thermal capacity of the water vapor. This heat is in no wise negligible, since to heat one molecular volume of water vapor from 0° to 1000° and from 0° to 1500° there are absorbed respectively 11 and 18 calories.

CALCULATION OF THE HEAT LOST AND UTILIZED IN A FURNACE FIRED WITH MIXED GAS, WITH RECUPERATION BY THE SECONDARY AIR ALONE.

Available Calories = 97.6.....	1000°	1500°
Calories carried away by the Products of $\begin{cases} CO_2 \\ 4 N_2 \\ \frac{1}{3} H_2O \end{cases}$	12.4	21.4
Combustion.....	29.7	46.0
	3.7	6.3
Total.....	45.8	73.7
Calories recuperated by the Secondary Air $\begin{cases} \frac{1}{2} O_2 + 2 N_2 \\ \frac{1}{2} O_2 + \frac{2}{3} N_2 \end{cases}$	18.5	28.9
from 0° to 1000° or 1500°.....	6.1	9.6
Total.....	24.6	38.5
Lost Calories.....	21.2	35.2
% of Lost Calories = P.....	22.0	36.0
% of Utilized Calories = U.....	78.0	64.1

In comparing these results with those above, we find that there is very little advantage in using mixed gas in the case of single

recuperation. The bettering of the recuperation coming from the increase of the secondary air is offset by the greater loss in calories in the waste products, due to the steam, the thermal capacity of which is very high. Thus, at  $1500^{\circ}$  the gain in calories is 3.3, and at  $1000^{\circ}$  only 2.1. This last figure is very interesting in connection with the furnace shown in Fig. 31, 32. It is seen that there is very little to gain by the use of steam for single recuperation. In the above deduction is found the explanation and confirmation of a practical fact already established.

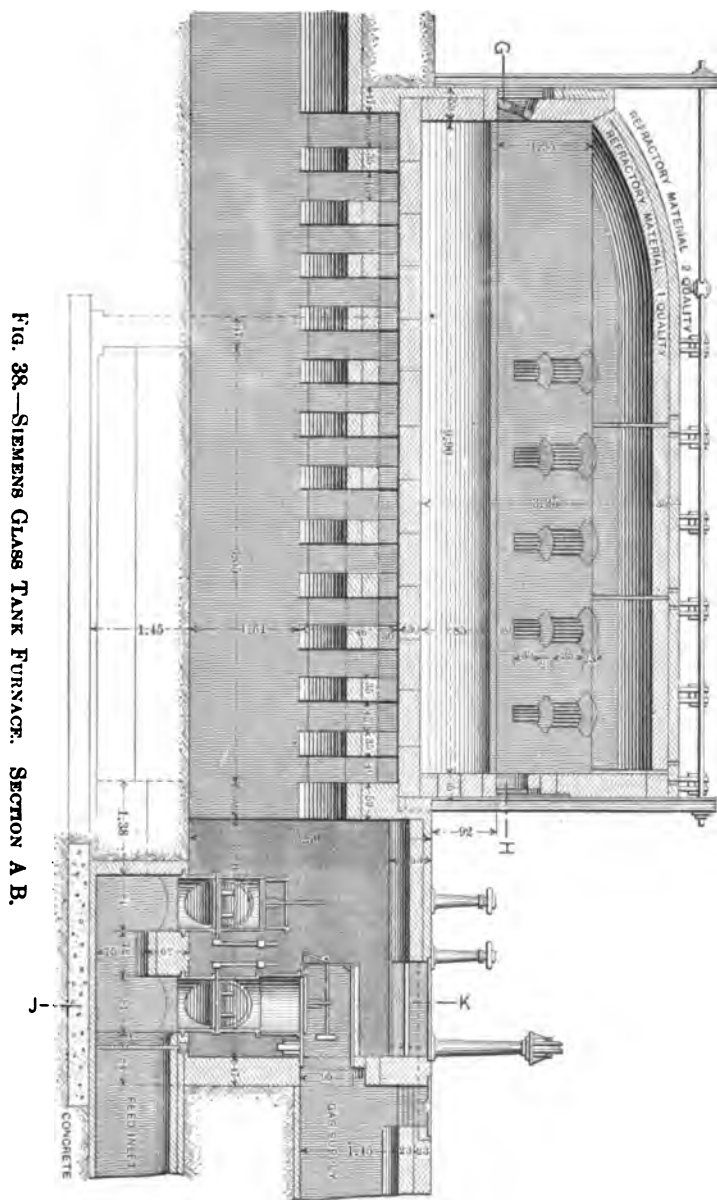


FIG. 37.—MORGAN SUSPENDED-ROOF BILLET-HEATING FURNACE.

*Second Case. Double Recuperation by Secondary Air and Gas.*—This case is the most important one in the theory of gas firing with mixed gas. Most Siemens furnaces for steel and glass use a gas enriched through the use of steam. The inclination to do away with the siphon accentuates further the tendency to use mixed gas, since by the use of steam the gas is cooled as well as enriched, in contradistinction to the effect of the siphon.

The interest of this case is further increased if we remember that it is always easy to pass from Siemens gas to mixed gas by slight modifications in the gas-producers.

In Fig. 38 is given an illustration of a tank furnace for glass



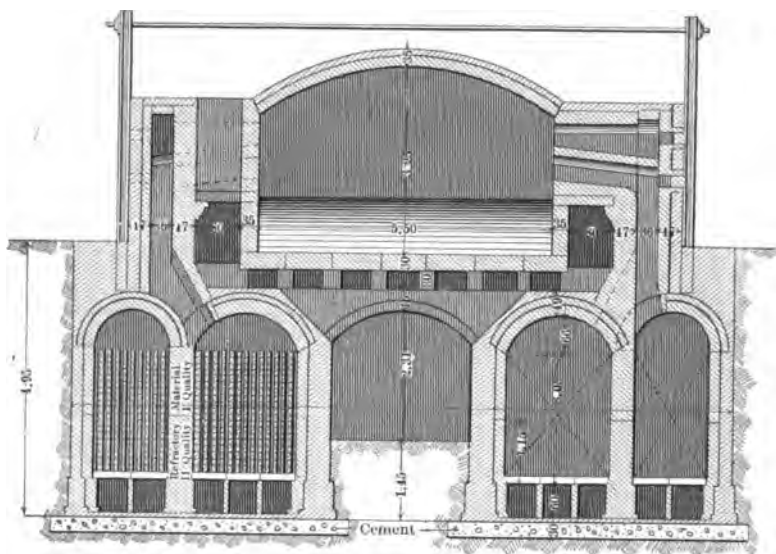


FIG. 38a.—SIEMENS GLASS TANK FURNACE. SECTION C D E F

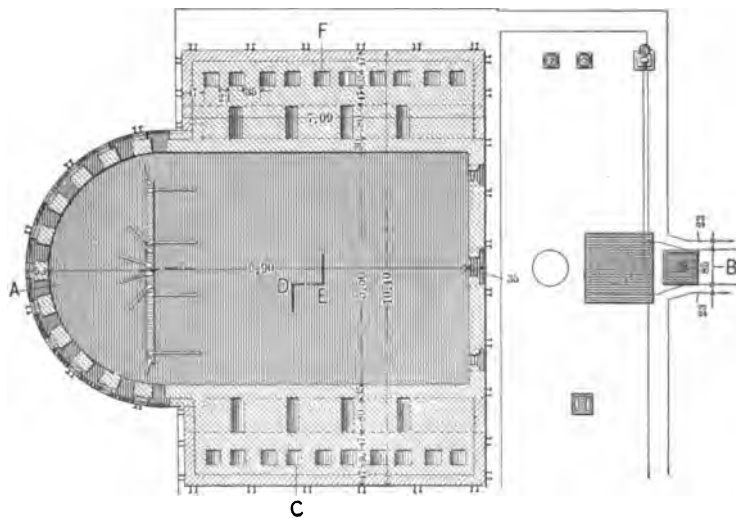


FIG. 38b.—SIEMENS GLASS TANK FURNACE. SECTION G H.



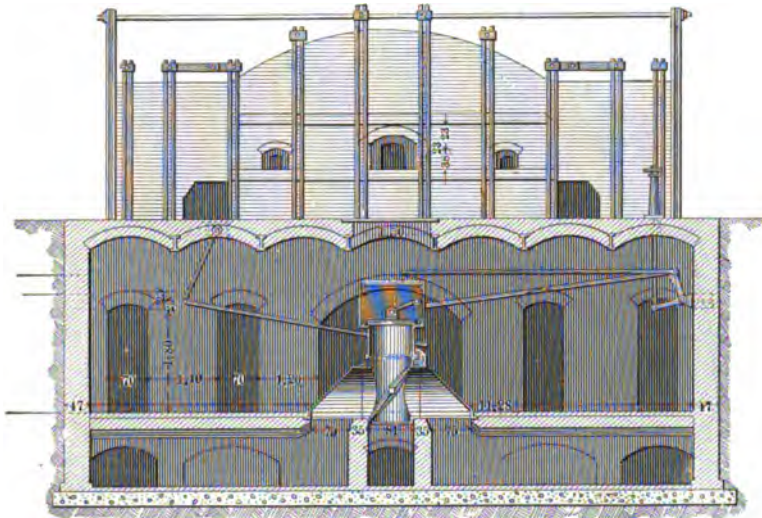


FIG. 38c.—SIEMENS GLASS TANK FURNACE. SECTION J K.

of 150 tons capacity. The producer is of the Siemens type, with water seal, and the producer-gas carries from 8 to 10% of hydrogen. The ruling temperature of the hearth is 1450°.

In order to find the value of the utilized heat, it is only necessary to add to the figures of the preceding case the number of calories taken up by the gas from 600° to 1000° or to 1500°.

CALCULATION OF THE HEAT LOST AND UTILIZED IN GAS FURNACES FIRED WITH MIXED GAS, WITH DOUBLE RECUPERATION BY THE SECONDARY AIR AND BY THE GAS, COMING AT 600° FROM THE PRODUCER.

Total available Calories = 97.6.....	1000°	1500°
Calories carried by the Combustion Products = F.....	45.8	73.7
Calories recuperated by the Secondary Air.....	24.6	38.5
Calories recuperated by the Gas = $\text{CO} + \frac{1}{2} \text{H}_2 + \frac{1}{2} \text{N}_2$ .....	6.3	19.7
Total Recuperated Heat = R.....	30.9	58.2
Calories lost = $F - R$ .....	14.9	15.5
% of Lost Calories $\frac{F - R}{97.6} = P$ .....	15.2	15.8
% of Utilized Calories = Efficiency = U.....	84.8	84.2

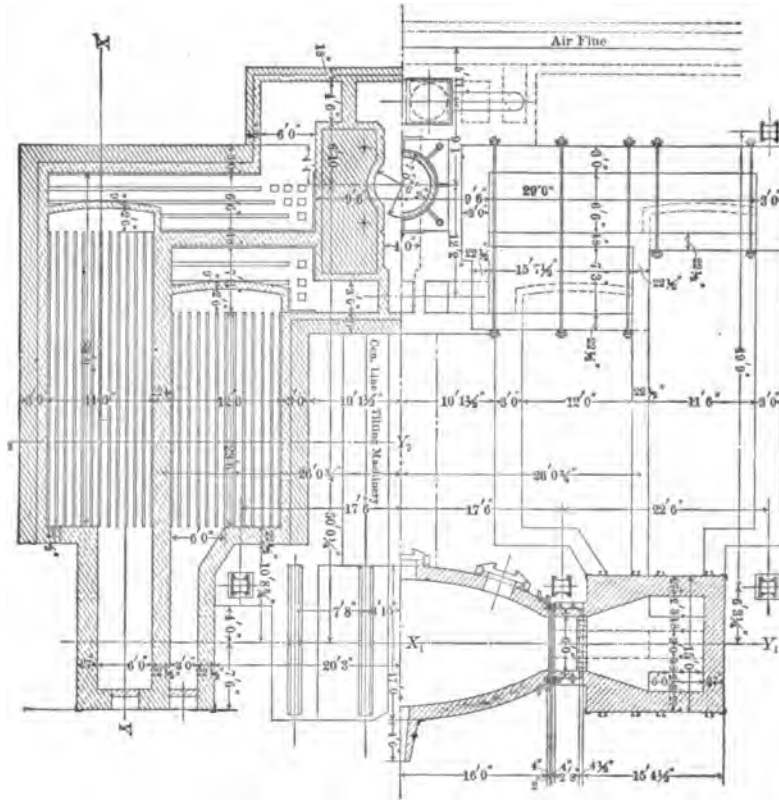


FIG. 39.—50-TON CAMPBELL BASIC FURNACE, STEELTON, PA.  
(From H. H. Campbell's "Metallurgy of Steel," Fig. VIII-C.)



The economy resulting from the double recuperation is apparent; for the temperature of  $1000^{\circ}$  the gain is  $84.8 - 75.7 = 9.1\%$ , and for the temperature of  $1500^{\circ}$  it is  $84.3 - 66.3 = 18\%$ , thus giving an economy of nearly one-fifth of the fuel. If we carry the temperature to  $1800^{\circ}$ , as in steel open-hearth furnaces, the economy will be over 25%.

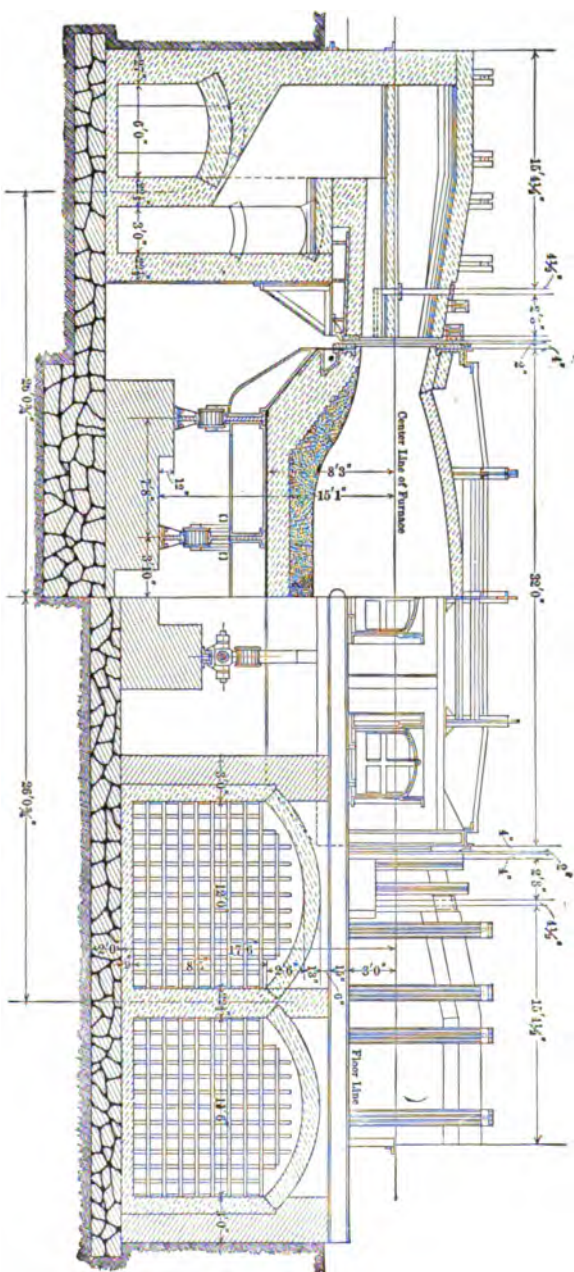
Such figures explain the favor with which the mixed gas was received from the first. We have seen that the higher efficiency is due wholly to the better recuperation. One-third more air is recuperated, and the gas has been recuperated from  $600^{\circ}$  to  $1290^{\circ}$ ; to this double recuperative gain is due the fuel economy, which we have seen may reach 25%.

*Third Case. Double Recuperation by the Primary Air and the Secondary Air; that is, Pre-heating of the Total Air.*—No complete application of this case is to be found in practice, since the producer grates would fail under the injection of the recuperated air. Some partial applications are embodied in the Klönne retort furnace as well as in many of the New Siemens furnaces, where a mixture of hot air and steam is injected together with some cold air, so that the temperature in the ash-pit shall not rise above  $500^{\circ}$ .

We give in Fig. 40 an outline drawing taken from the English patent of Henry; it is the Klönne system, applied to a gas-retort furnace. The recuperation takes place in two chambers by the parallel counter-current system, one chamber being used for the primary air, the other for the secondary. We have seen that by pre-heating the primary air to  $1000^{\circ}$  and to  $1500^{\circ}$ , the amount of water gas can be raised respectively to 48 and to 54%.

CALCULATION OF LOST AND UTILIZED HEAT IN GAS FURNACES FIRED WITH MIXED GAS WITH DOUBLE RECUPERATION: TOTAL AIR. THE GAS PRODUCER IS MAINTAINED AT  $600^{\circ}$  C.

Available Calories = 97.6.....	1000°	1500°
Calories carried away by the Combustion Products = F.....	47.4	77.5
Calories recuperated by the Total Air = R.....	37.0	57.8
Calories lost = F - R.....	10.4	19.7
Loss, % $\frac{F-R}{97.6}$ P.....	10.6	20.2
Utilized Heat, Efficiency = U.....	89.4	79.8



SECTION X<sub>1</sub>-Y<sub>1</sub>

SECTION X<sub>2</sub>-Y<sub>2</sub>

Fig. 39b.—50-Ton CAMPBELL BASIC FURNACE, STEELTON, PA.  
(From H. H. Campbell's "Metallurgy of Steel," Fig. VIII-C.)

The heat utilization is very good for all temperatures, and it compares favorably with the double recuperation by air and gas. These results show that there is much to be expected from the application of this system.

The recuperation by the total air has the great advantage of reducing the number of the chambers to two, from which the primary and the secondary air may be drawn. The better efficiencies shown by the total recuperation of the air in the case of the Siemens gas can be foreseen, since the steam used in the case of the mixed gas carries to the stack, without any possible return, all the calories necessary for its heating to the ruling temperature of the hearth.

It should not be concluded, however, that the mixed gas is without interest in the case of recuperation by the total air, since without steam the temperature of the producer would become prohibitory; the dissociation of the steam used lowers the temperature to a point where it seems that practical application should not be impossible. We are brought to the dilemma of either finding means of preserving the grate or using the Ebelen type of producer. The New Siemens furnace is well suited to the adoption of the pre-heating of the total air.<sup>1</sup>

*Fourth Case. Triple Recuperation by the Primary Air, Secondary Air and Gas.*—This case to our knowledge has not received any industrial applications. It would necessitate three recuperators, the third recuperator to collect the heat left in the products of combustion after pre-heating the secondary air and gas. We have seen (page 105) that there is left of the heat 15.2 and 15.8%, at 1000° and 1500° respectively. In spite of its complexity, this system is worthy of serious consideration, especially for very high temperatures, on account of the high efficiencies it gives. In fact, they have reached the very limit of the utilization of the heat of the fuel, the remaining 6% being required for the draught in the chambers. From the point of view of recuperation alone, the limit is

<sup>1</sup> Many trials have been made in this direction, especially by F. Siemens, who designed a producer without a grate in which the coal took its own angle of repose. The problem is, however, far from solution, since we do not know of any producer in which the temperature at the ash-pit is ever as high as 450°, and beyond this temperature the producer does not work satisfactorily. There is still a large gap to be crossed; the recuperation cannot be considered as complete below 1000° C. under the ash-pit.

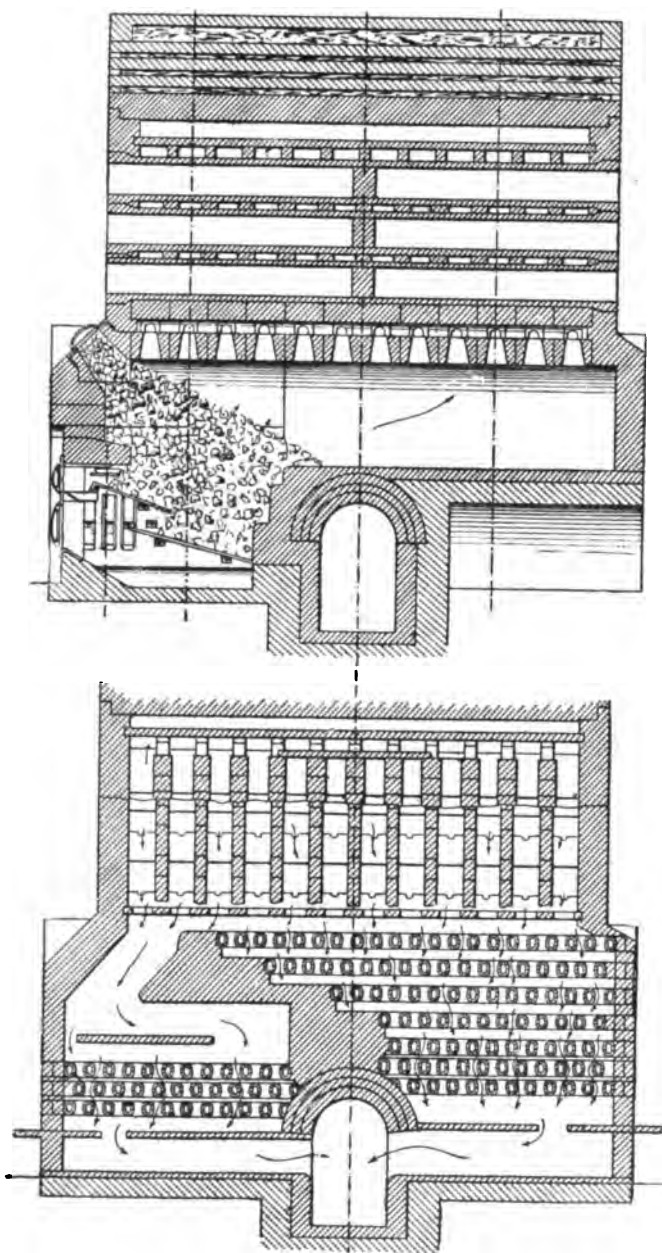


FIG. 40.—KLÖNNE RETORT FURNACE.

even exceeded in a sense, since the mass of the recuperating gases is larger than the mass of the waste products. The primary air passes twice through the chambers—once in the primary air recuperator and a second time in the gas recuperator. The products of combustion, on the contrary, travel but once through the recuperators, and furthermore their thermal capacity is less than the combined thermal capacities of the total air and of the gas.

CALCULATION OF THE LOST AND UTILIZED HEAT IN GAS FURNACES FIRED WITH MIXED GAS WITH TRIPLE RECUPERATION.

	1000°		1500°	
	48 % Water Gas 52 % Siemens Gas Gas :		54 % Water Gas 46 % Siemens Gas Gas :	
Available Calories = 97.6 .....	CO + .48H <sub>2</sub> + 1.04 N <sub>2</sub> Waste Products: CO <sub>2</sub> + 4N <sub>2</sub> + .48 H <sub>2</sub> O		CO + .54 H <sub>2</sub> + .92 N <sub>2</sub> Waste Products: CO <sub>2</sub> + 4N <sub>2</sub> + .54 H <sub>2</sub> O	
Recuperation from .....	1000° to 600°	600° to 0°	1500° to 600°	1600° to 0°
Thermal Capacities of the Waste Products = F .....	21.7	26.5	50.0	26.8
Available Calories for Recuperation by the Total Air .....	15.6	21.5	36.4	21.5
Available Calories for Recuperation by the Gas at 600° .....	7.8	0.0	17.9	0.0
Total = R. ....	23.4	21.5	54.3	21.5
Excess of the Thermal Capacities of the Recuperating Gases over that of the Products of Combustion .....	1.7 <sup>1</sup>	.....	4.3 <sup>2</sup>	.....
Excess of the Thermal Capacities of the Products of Combustion over that of the Recuperating Gases = F - R .....	.....	5.0	.....	5.3
% of Loss = P .....	.....	5.1	.....	5.4
% of Utilized Heat = U .....	94.9		94.6	

<sup>1</sup> The recuperation limit being exceeded by 1.7 Calories between 1000° and 600°, the recuperation is perfect.

<sup>2</sup> The recuperation limit being exceeded between 1500° and 600°, the recuperation is perfect.

Under such conditions, it might appear that perfect recuperation—an efficiency of 100%—should result. This, however, is evidently not the case, as it is easy to understand when it is re-



membered that only from  $0^{\circ}$  to  $600^{\circ}$  the total air takes part in the recuperation, and that its thermal capacity is less than that of the waste products. Therefore, between  $0^{\circ}$  and  $600^{\circ}$  there is <sup>7</sup><sub>2</sub> a loss, which is absolute, not being compensated in the next step—from  $600^{\circ}$  to the ruling temperature  $1000^{\circ}$  or  $1500^{\circ}$ —in which the thermal capacity of the recuperating gas is larger than that of the products of combustion.

It follows that, in order to be able to calculate the heat utilization, it is necessary to operate in two stages—one from  $0^{\circ}$  to  $600^{\circ}$ , the other from  $600^{\circ}$  to the ruling temperature,  $1000^{\circ}$  or  $1500^{\circ}$ .

As an application of the triple recuperation of the gas, secondary air and primary air, the system of A. L. Queneau may be mentioned.

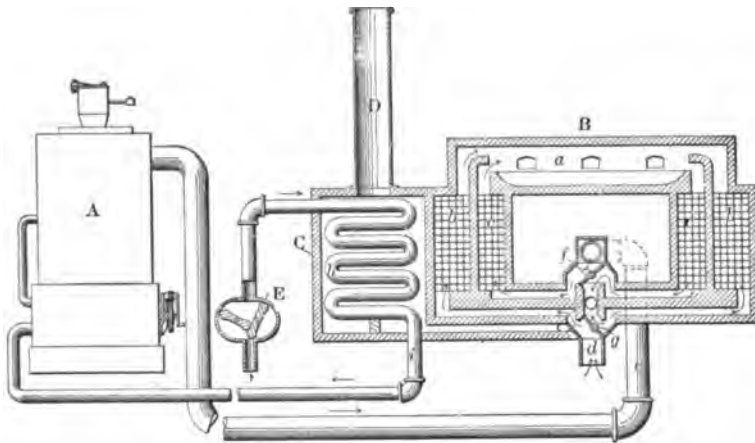


FIG. 41.—QUENEAU SYSTEM OF TRIPLE RECUPERATION OF THE PRIMARY AIR, SECONDARY AIR AND GAS.

It has the ordinary Siemens chambers for the gas and secondary air, with a single chamber of the parallel counter-current type for the primary air. Usually the waste products leave the Siemens chambers on their way to the stack at a temperature which allows the use of cast-iron pipes for the recuperator. In case of high temperatures a firebrick recuperator is used.

The primary air recuperator is designed so that the waste products leave it at a temperature of about  $200^{\circ}\text{C}$ ., a temperature

necessary for an efficient draught in the stack. The primary air is forced through the recuperator by means of a positive blower, while the heated air is led to the producer through a brick-lined flue. In order to utilize the calories of the primary air to the best advantage, without endangering the producer, the primary air meets a system of water sprays (the steam injector being entirely dispensed with). The vaporization of the water injected is obtained wholly at the expense of the recuperated waste heat (doing away with the boiler plant). By injecting the water in liquid form in the producer and obtaining its vaporization thereby, the fire zone of the producer is cooled more efficiently than by steam injection. The amount of injected air and water can be varied independently at will, since they are not interdependent, as in the case of the steam injector. The use of the parallel counter-current system for the primary air does away with the complications of a third set of valves. The regulation of the temperature of the primary air recuperator is automatically obtained by the regulation of the temperatures in the Siemens chambers. Fig. 41 shows the application of the system to an open-hearth furnace. The drawing is taken from the patent specifications. The calculations are shown above.

From an examination of the table two conclusions may be made.

- (1) The very high efficiency of furnaces with triple recuperation.
- (2) The very small influence of the ruling temperature on the heat utilization.

This system of recuperation is, then, particularly suited to high temperatures; its use would result in a fuel economy of 10% over that of the Siemens furnace.

There is a last case where the use of triple recuperation would give an economy even greater than 10%; it is in its application to industrial operations, in which the waste products consist of the products of combustion of the fuel, and of gases liberated by the materials under treatment in the hearth—that is, water vapor, carbon dioxide, sulphurous dioxide, etc. In the various systems already reviewed, the calories carried by these gases would be utterly lost, since the products of combustion of the fuel have higher

thermal capacities than the recuperating gases. In the case of triple recuperation the contrary is true, and therefore these extra calories can be brought back to the hearth.

Glass furnaces present the typical example of this supplementary recuperation. The materials charged in the furnace carry as much as 45% of volatile products; the coal required for the fusion of the glass weighs about 60% of the weight of the fused glass. The mass of the volatile products is, therefore, mathematically speaking, a quantity of the same order as that of the products of combustion of the fuel. The ratio of the masses may be as high as  $\frac{1}{20}$ , corresponding to a loss of  $\frac{1}{20}$  of the available calories. The recuperation of these lost calories, added to the increased economy resulting from triple recuperation proper, would bring an increase of 15% in the fuel efficiency by the application of this system to glass furnaces.

In summing up the problem of the application of mixed gas to furnace firing, it may be said that single recuperation is suited only to high-temperature furnaces; it is very advantageous to all furnaces with double recuperation, and in the case of triple recuperation it offers the maximum efficiency to be expected, irrespective of the ruling temperatures.

## CHAPTER VII.

### FURNACES MAKING USE OF THE SO-CALLED REGENERATION OF THE PRODUCTS OF COMBUSTION—NEW SIEMENS FURNACE—USE OF PURE CARBON DIOXIDE IN GAS-PRODUCERS.

*Reactions of Combustion.*—General attention has been called to the regeneration of the products of combustion owing to the introduction of the New Siemens furnace, in which this principle receives a partial application. The furnace is so designed that the injection of the waste products in the gas-producers can be accomplished to any extent desired.

A number of years before Biedermann and Harvey secured their patent, E. Göbbe had received a patent covering the introduction of products of combustion in the ash-pit of gas-producers. He was not able, however, to make a practical application. It is only since 1893 that furnaces, based on the principle of the regeneration of the products of combustion, have been constructed.

It has been proposed also to inject pure carbon dioxide in gas-producers, the carbon dioxide being taken from lime-kilns, for example. No applications of this idea, which is, however, a rational one, are known; the difficulty, evidently, is to obtain carbon dioxide free from nitrogen without undue cost.

Thus, theoretically, we have two cases to examine:

- (1) Injection of the production<sup>s</sup> of combustion.
- (2) Injection of pure carbon dioxide.

The results of the use of carbon dioxide have been studied (page 63); we have seen that it acts precisely as steam:

- (1) By decreasing the amount of the primary air.
- (2) By lowering the temperature of the gas, on account of the heat absorbed in its decomposition.

$C + CO_2 = 2 CO$  with the absorption of 38.8 calories per molecular volume; the cooling action of the steam is thus less efficient by a difference of  $38.8 - 28.8 = 10$ . calories. If, however, the vaporization of the steam is effected in the producer itself, at the expense of its sensible heat, the efficiency of steam is equal to that of carbon dioxide. Like steam, carbon dioxide cannot furnish any calories, and its use does not increase the number of available calories.

*First Case. Injection of Pure Hot Carbon Dioxide in Gas-Producers.*—This case does not properly belong to the study of heat recuperation, since the injection of hot carbon dioxide constitutes an addition to the available calories of the fuel. We shall examine it, however, as it represents the only true case of carbon regeneration. Let us suppose that, close by the gas-producer, we have a supply of pure carbon dioxide at  $1000^\circ C$ . To calculate the maximum economy to be realized, we have only to consider that the whole of the sensible heat of the carbon dioxide is made use of in the regeneration of the carbon. It suffices to calculate the amount of carbon dioxide that can be injected at  $1000^\circ$  in the producer without lowering its temperature below  $600^\circ C$ . The calculation is precisely the same as in the case of steam.

Let "m" be the proportion of carbon gasified by the carbon dioxide in the total amount (12 grams) of the burned carbon.

$$m (C + CO_2) = 2mCO$$

liberating  $m (-38.8 + 12.7)$  calories, 12.7 being the thermal capacity of a molecular volume of carbon dioxide from  $0^\circ$  to  $1000^\circ$ .

$$(1 - m) (C + \frac{1}{2} O_2 + 2N_2) = (1 - m) (CO + 2 N_2)$$

liberating  $(1 - m)$  29.4 calories.

The chemical composition of the gas will be

$$(1 + m) CO + (1 - m) 2N_2$$

of which the thermal capacity from  $0^\circ$  to  $600^\circ$  is  $(3 - m)$  4.3 calories. Hence the equation:

$$\begin{aligned} -26.1 m + 29.4 (1 - m) &= (3 - m) 4.3 \\ m &= .33 \end{aligned}$$

One-third of the fuel will, therefore, be gasified by the carbon monoxide, the remaining two-thirds by the air. The resulting economy will be, per molecule of burned carbon, one-third the

thermal capacity of carbon dioxide from  $0^{\circ}$  to  $1000^{\circ}$ , or  $\frac{12.7}{3}$ ;

in percentage, the economy is  $\frac{12.7 \times 100}{3 \times 97.6} = 4.3\%$ .

Evidently to this economy is to be added that resulting from a better recuperation, as in the similar case of the mixed gas group, and that due to the lack of latent heat of vaporization. Nevertheless, the advantages accruing from the use of pure carbon monoxide are not sufficiently large to warrant many trials of application.

*Second Case. Injection of Hot Products of Combustion in the Gas-Producer.*—The injection of the waste products in the gas-producers, like the mixed gas, may be applied to the four methods of recuperation.

As the applications of this system are limited, and further since two of the cases—namely, that of the triple recuperation and that of double recuperation by secondary air and gas—have never been attempted, it will suffice to condense in one table the results of all the calculations.

The carbon dioxide taken from the waste products is accompanied by a volume of nitrogen, which is the same for all furnaces in which carbon is the fuel. This very large volume of nitrogen increases to a marked degree the amount of sensible heat going to the producer. It follows that it is possible to send to the producer a much larger volume of carbon dioxide than could be done with steam or pure carbon dioxide without lowering the temperature of the producer below  $600^{\circ}$ . The other conditions being the same, the influence on the recuperation will be correspondingly increased. A simple calculation shows that, when the waste products are injected at  $1450^{\circ}$ , no more primary air is required; all the air will be secondary. At  $1000^{\circ}$  it will be possible to send 44% of carbon dioxide.

Under the above condition its use will result in a great improve-

ment of the efficiency. It must be remembered, however, that this latter is due wholly to better recuperation, by the increase in the secondary air and the cooling of the gas, and that no gain whatsoever comes from the so-called carbon regeneration, and furthermore that there is no increase in the number of available calories.

CALCULATIONS OF THE EFFICIENCIES OF FURNACES FIRED WITH GAS OBTAINED FROM PRODUCERS INJECTED WITH PART OF THE PRODUCTS OF COMBUSTION.

Available Calories = 97.6 - Q	Recuperation by the Secondary Air		Double Recuperation by Air and Gas		Double Recuperation by Total Air		Triple Recuperation	
	1000°	1500°	1000°	1500°	1000°	1500°	1000°	1500°
Thermal Capacities of the Products of Combustion = F	42.1	67.5	42.1	67.5	42.1	67.5	42.1	67.5
Calories Recuperated by Pre-heating the	Secondary Air		Primary Air		Gas			
	26.5	57.8 <sup>1</sup>	26.5	57.8 <sup>1</sup>	37.0	57.8 <sup>1</sup>	37.0	57.8 <sup>1</sup>
Total P.....	26.5	57.8	34.0	65.1	37.0	57.8	42.1	65.1
F - R = Calories Lost.....	15.6	9.7	8.1	2.4	5.1	9.7	2.4	2.4
% of Lost Calories $\frac{F-R}{Q} = P$	16.0	10.0	8.5	2.5	5.6	10.0	2.5	2.5
% of Utilized Heat, Efficiency = U.....	84.0	90.0	91.5	97.5	94.4	90.0	97.5	97.5
Remarks.....	<sup>1</sup> Total Air: see page 116.		<sup>1</sup> Total Air. <sup>2</sup> The Recuperation limit is exceeded; the gas could absorb at 1000° 15.12 Cal.; at 1500° 44.4 Cal. if the equivalence of the Masses did not limit the Recuperation.		<sup>1</sup> Total Air.		<sup>1</sup> Total Air. <sup>2</sup> The Recuperation limit is exceeded; the gas could absorb at 1000° 13.4 Cal. and at 1500° 44.4 Cal. if the equivalence of Masses did not limit the Recuperation.	

The efficiencies given above are remarkable; they are better than most of the corresponding cases of the Siemens and of mixed gas firing. This is to be expected, since the hot waste products

have a greater effect on the recuperation per molecular volume, and the mass of the waste products is not increased by their use, causing a useless waste of calories to be discharged into the atmosphere.

However, it must be remembered that this class of furnace is, on the whole, entirely theoretical. Only single recuperation and that of the total air have been attempted,<sup>1</sup> and that only to a small extent, by using but a trifling part of the available waste products. The question of the preservation of the grate prevents any more complete application.

We have greatly simplified the treatment of the problem by assuming the absence of the large amount of steam required for the injection of the waste products into the producer. If we take the case of the New Siemens furnace we see (Fig. 17) that it is provided with three Koerting injectors, one in communication with the waste products flue, the second with the air chamber, the third with the atmosphere. The large amount of steam used reduces very largely the amount of waste products that could be used; it therefore brings this furnace very close to that of a furnace fired with mixed gas with secondary air recuperation and partial primary air recuperation. The saving in fuel that this furnace has given in many instances is probably due to the very happy grouping of all the organs, the radiation losses being reduced in a large degree.

If we take the case of a New Siemens furnace with a ruling temperature of 1000°, the heating of the primary air gives a maximum efficiency of 75.7% with Siemens gas, of 78% with mixed gas, and of 84% with the injection of the waste products. The recuperation of the secondary air brings the efficiencies respectively to 94.8, 89.4, 94%. The efficiency of the New Siemens furnace should lie in an intermediate position with regard to these various figures. It may be safely said that this furnace will have a slightly better efficiency than either of the other two cases with simple recuperation.

In the case of the Siemens gas, when the total air is pre-heated the same efficiency—namely, 94%—is attained as with the in-

<sup>1</sup> F. Siemens has since patented a four-chamber regenerative furnace with injection of waste products corresponding closely to the total recuperation by primary air, secondary air and gas.



jection of the waste products; therefore it is rational to inject into the producer an equal volume of waste products and heated air. The superiority of the New Siemens furnace is not so much due to the so-called regeneration of the carbon dioxide as to the total heating of the air. In any event, for medium temperatures this furnace is better than any other type of furnace using single recuperation.<sup>1</sup>

At 1500° single recuperating furnaces have efficiencies of 60.50 and 64.11% when fired with Siemens and mixed gas respectively. Double recuperating furnaces fired with mixed gas give 84.3%. The difference between these efficiencies is too large to be overcome by the partial application of the so-called regeneration of the products of combustion. At this ruling temperature the New Siemens furnace may give better results than the first Siemens furnace with air siphon when fired with Siemens gas; but it will not equal that of furnaces with double recuperation fired with mixed gas.

The New Siemens furnace is of a construction more economical than furnaces with double recuperation; it is better adapted than any other to furnaces of small capacities; and its regulation is easier than that of furnaces with natural draught. These are advantages of enough importance under industrial conditions without *a priori* giving to the furnace a better fuel utilization, which theory disproves and which practice has not as yet shown.

<sup>1</sup> When, as in present practice, only one-fifth of the available waste products is injected into the gas producer, the accrued economy is very low, from 1 to 3%. This may be verified by a simple calculation. If, besides, the waste products are cooled, the resulting economy is practically nil.—*Translator*.

## CHAPTER VIII.

### CLASSIFICATION OF THE VARIOUS TYPES OF FURNACES.

In Table 11 we give a résumé of the preceding chapters. This table gives the absolute value for the maximum heat utilization in the furnaces, from the purely theoretical point of view, without taking into account their degree of practicality. Therefore, from such tables we should not deduct the classification of the furnaces by merely taking into consideration the value of the utilized heat  $U$ . The classification so made would be exact only for furnaces capable of complete industrial application; for all the other cases there is room for discussion.

On this basis, we will review briefly the foregoing study.

*For a temperature of 1500° and higher*, the best furnace in use today, from the point of view of the utilization of the heat of the fuel, is the Siemens furnace, with double recuperation by the secondary air and gas when fired with mixed gas, the producer not having a siphon. Its recuperative efficiency is 85%.

By pre-heating the primary air it would still be possible to gain a further 10%, since the limit of the triple recuperative furnace is 95%. The pre-heating of the primary air for such furnaces would be less difficult than for furnaces with simple recuperation, as heating the air to 800° would be sufficient to secure the 10% increased efficiency.

This improvement, to be realized by the triple recuperation with mixed gas without siphon, would give a perfect utilization of the available calories of the fuel and be a solution of the problem which might be considered as final.<sup>1</sup>

<sup>1</sup> Let us recall that the triple recuperation furnace presents a special interest in the case where to the mass of the products of combustion comes an additional gaseous mass, issuing from the material worked on the hearth, as in glass furnaces. We have seen that the supplementary efficiency which would result is 3 to 4%. In this special industry a saving of 10 to 14% could be secured. This is a very appreciable advantage, since the heating is continuous and the cost of the fuel is a very important item in the cost of production.

With marked inferiority follow the furnaces with double recuperation fired with Siemens gas, with an efficiency of 66%, closely followed in turn by the furnaces with single recuperation of mixed gas with 64%, and lastly the furnaces with single recuperation of Siemens gas with 60%.

The furnaces with injection of the products of combustion into the producer have not been included in the preceding classification, since their industrial applications are very limited as yet; all that can be said of them is that they are superior to the last two types mentioned. In their present condition—that is, with a temperature in the ash-pit of 400° to 500°—they can give a better efficiency than the original Siemens furnace, but they are inferior to the Siemens furnace fired with mixed gas.

The classification may then be condensed as follows:

- (1) Mixed gas furnaces with triple recuperation.
- (2) Mixed gas furnaces with double recuperation by secondary air and gas.
- (3) (a) Siemens gas furnace with double recuperation by air and gas.  
(b) Furnaces with injection of waste products into the producer (New Siemens furnace).
- (4) Mixed gas furnace with single recuperation.
- (5) Siemens gas furnace with single recuperation.
- (6) Direct-fired furnaces.

*In the case of medium temperature furnaces, say 1000°, the best furnace is also the double recuperative furnace fired with mixed gas, but it does not appear that the double recuperation has here a very great advantage. The difference in efficiency between a furnace with one pair of chambers (78%) and that of a furnace with two pairs (85%) is too small to warrant the increased cost and complexity of construction; the additional radiation from the extra pair of chambers may offset the difference. For such temperatures furnaces with one pair of chambers are to be preferred.*

TABLE 11.

COMPARATIVE TABLE OF ALL SYSTEMS OF FURNACES AT RULING TEMPERATURES OF 1000° AND OF 1500°

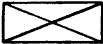
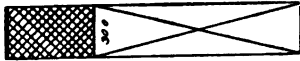
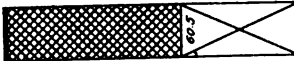


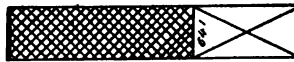
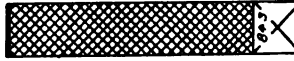






Maximum Utilized Heat - U



Classification	1000° Diagrams of the Percentage of the Heat Lost - P and Utilized - U	Industrial Applications
Direct firing.....		Copper furnaces, Boëtius, Bicheroux furnaces.
Siemens gas.....		Retort furnaces for illuminating gas.
		No possible applications.
		Partial application in some retort furnaces.
Mixed gas (Siemens with the permissible maximum water gas)		Retort furnaces, Siemens, Lencaches furnaces for brass, etc.
		Siemens furnace.
		Partial application in Klönne retort furnace.
		No applications.
Siemens gas with the permissible maximum of regenerated products of combustion.....		Partial application in the New Siemens.
		No applications.
		Partial application in the New Siemens.
		No applications.

*Remark.*—Direct, Siemens gas and mixed gas firing have received complete industrial applications.

TABLE 11 (Concluded)

Minimum Lost Heat = P 		
Method of Recuperation	1500° Diagrams of the Percentage of the Heat Lost = P and of the Heat Utilized = U	Industrial Applications
No recuperation.		Puddling furnaces, glass and ceramic furnaces.
Single recuperation by the secondary air.		Glass open-hearth fur- naces.
Double recuperation = secondary air, gas.		Martin - Siemens fur- naces for steel, glass, etc.
Double recuperation = secondary and prim- ary air.		No applications.
Single recuperation by the secondary air.		Glass open-hearth fur- naces.
Double recuperation = secondary air, gas.		Siemens furnaces.
Double recuperation = secondary and pri- mary air.		Partial application in the New Siemens.
Triple recuperation = secondary and pri- mary air, gas.		No applications.
Single recuperation by the secondary air.		Partial application in the New Siemens.
Double recuperation = secondary air, gas.		No applications.
Double recuperation = secondary and pri- mary air.		Partial application in the New Siemens.
Triple recuperation = secondary, primary air and gas.		No applications.

The applications of the various cases of the so-called regenerated products of combustion are either very imperfect or wanting; their classification offers, therefore, only a theoretical interest.

Today most of the furnaces with the ruling temperature of  $1000^{\circ}$  have single recuperation by secondary air alone, and are fired either with Siemens or mixed gas. We have seen that theoretically the two systems are equivalent at the temperature under consideration, and the selection to be made depends very much on the character of the fuel.

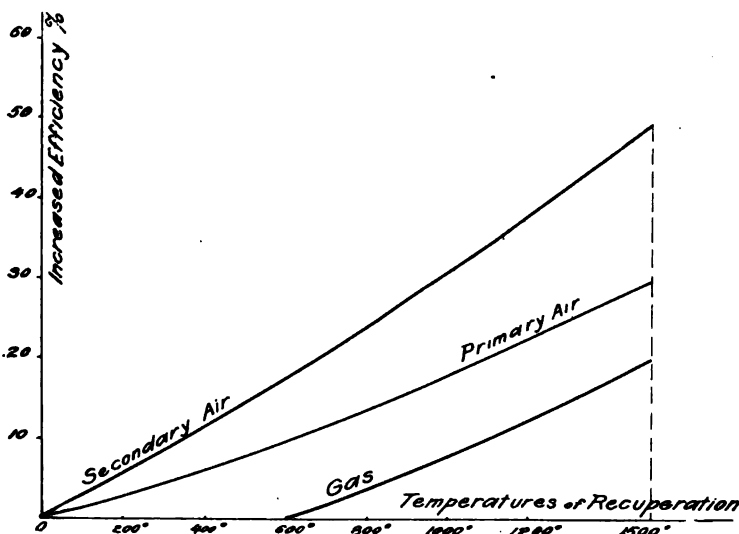


FIG 42.—CURVES SHOWING, FOR DIFFERENT TEMPERATURES, THE THEORETICAL ECONOMIES OCCURRING FROM THE PRE-HEATING OF THE PRIMARY AIR, SECONDARY AIR AND GAS.<sup>1</sup>

It would be advantageous, however, if practical obstacles do not block the way, to introduce a system allowing the pre-heating of the primary air without increasing the number of the chambers, as in the Klönne furnace,<sup>2</sup> or to send back under the grate part of the waste products, or to do both, as is done in the New

<sup>1</sup> Evidently the various economies are cumulative for a given temperature. Thus, if at a ruling temperature of  $1,000^{\circ}$  all three gas-currents are pre-heated, the total resulting economy is  $17+8+30=55\%$  of the fuel which would be used if no recuperation was obtained.

<sup>2</sup> See page 111.

Siemens furnace. For our purpose these various improvements tend toward the same end—a maximum efficiency of 94%; in the case of a partial application the various efficiencies would be about equal.

All these applications are barred at present by the unsolved problem of the preservation of the grates. In supposing that the primary air is heated only to 400°, the economy to be realized would be 6%; this is not negligible in the case of continuous furnaces, as those for illuminating gas.

The classification of furnaces for temperatures of about 1000° is, then, as follows:

- (1) Furnaces with double recuperation by primary air and secondary air, or with injection of waste products in the producer (New Siemens furnace).
- (2) Mixed gas furnace with single recuperation.
- (3) Siemens gas furnace with single recuperation.
- (4) Direct-fired furnaces.

We may finally remark that, for the industries using furnaces with the ruling temperature of 1000°, with direct firing, it would be a decided advantage to replace them by gas-fired furnaces, for there is thus an economy of 30% certain of realization. There remain still today many such industries in which the introduction of gas firing would result in increased fuel efficiencies. It is hard to understand because of such certainty why direct-fired furnaces are still in operation, unless it be that it is more difficult to find competent men to operate gas furnaces than men skilled in the running of direct-fired furnaces.

*For low temperatures*, especially for steam boilers, there is little to expect from gas recuperation; the progress to be made lies in the more complete combustion of the fuel, without a great excess of air.

The progress to be realized in industrial heating theoretically is not enormous. It means a saving of from 10 to 15% of the fuel in increased efficiency over the present best practice. This, however, is worthy of serious consideration under modern industrial conditions.

The successful introduction of gas firing depends largely on the appreciation from the industrial world of the technical problems involved in the design of gas furnaces and in the knowledge of the science of their practical operation.

The preceding theoretical study has shown the maximum efficiencies that could be expected from the various systems. The experimental testing of these efficiencies will be treated in the following chapters.



## CHAPTER IX.

### EXPERIMENTAL STUDY OF THE HEAT UTILIZATION IN FURNACES.

The experimental determination of the heat efficiency of a furnace should be obtained by following the method pursued in the theoretical study which gave the general classification of all systems of recuperative heating. The starting point of any such investigation will evidently be the exact determination of the available calorific power of the fuel. This will serve as a term of comparison for all the quantities of heat lost and utilized in the various organs of the furnaces. In respect to these thermal quantities, we will be able to make their determination when we know the chemical composition and the temperature of the gases at the various points of division of the furnaces.

If the scientific data which have enabled us to conduct our theoretical examination are recent, still more so is the apparatus that may be used for the accurate experimental determination. The Mahler calorimeter which has rendered practical the Berthelot calorimetric method was not brought out before 1892, and the thermo-electric Le Chatelier pyrometer dates from 1889.

*Heat Balance-Sheets of Furnaces.*—The experimental determination of the heat balance-sheet of a furnace has for its purpose the estimation of the ratio of the heat utilized in the hearth to the total available heat; also the values of the various heat losses; and, finally, the quantity of heat recuperated.

The value of a furnace can be determined with accuracy only through such tests, and if the efficiency is found wanting it will be possible to find the reason therefor. They are, for furnaces, the equivalent of the complete tests which are made so frequently and with such good results on steam engines. Nevertheless, very few have been the number of complete tests made on furnaces,

hence it is difficult to make a well based comparison between the various systems of heat recuperation and the different types of furnaces suited to a given industry. This lack of experimental data is detrimental to progress. The example set by steam engineers should be followed by the men who have charge of gas-fired furnaces.

It will be seen in Part II that the apparatus needed for the experimental determination of heat balance-sheets is simple as well as practical; we will show, by a typical example, that the work presents no special difficulties. The selected case is one of the more complex examples offered by works—that of a Siemens furnace fired with mixed gas, with double recuperation by air and gas.

*Experimental Methods.*—The determination of a heat-balance sheet requires the following:

- (1) Heat utilized.
- (2) Heat carried away by the waste products.
- (3) Heat lost in the gas-producer by conductivity or radiation.
- (4) Heat lost by the radiation of the chambers.

The sum of these four quantities of heat, taking our definition of the limits of the various organs, must be equal to the total available heat—that is, to the calorific power of the fuel. It follows that one of these four quantities can be determined by difference when the other three quantities are known; we will thus be able to make an accurate determination of the heat lost by the radiation of the recuperative chambers. This heat lost escapes any direct determination on account of the double action suffered by the traversing gases, heating or cooling by the checker work and cooling by the enclosing walls. A quantity of heat useful to determine is the amount of the recuperated heat, though it does not enter directly into the heat balance-sheet. It can be measured with accuracy in function of the temperatures and composition of the gases. This will give us the only exact means of comparison between the various systems of recuperation.

If it is desired to obtain an absolutely exact test, it is necessary to weigh exactly the amount of coal, steam and water used in the

producers, beside making the usual gas analyses and heat determinations. It will then be possible to control synthetically the gas analyses. The test in this case must be made to cover a sufficient length of time, so that the weights of the coal and water may be accurate; the samples of gases are to be taken often enough to represent a fair average during the total length of the experimental period of time.<sup>1</sup> The samples of the coal used for the ultimate analysis and for the determination of the calorific power are to be taken from the fuel as it is charged in the producers. Twenty-four hours at least are required, and better 36 in the case of large producers.

The direct measure of the steam and water used is, however, not necessary for most tests. The determinations based on the temperature measurements, gas and coal analyses and determination of the calorific power of the coal are sufficient, if careful weights are taken of the fuel burned for 36 hours, and of the ashes produced during a corresponding period.

*Experimental Data Required for the Calculation of the Heat Balance-Sheet of a Siemens Furnace with Double Recuperation, Fired with Mixed Gas.*—The experimental data required are the following:

- (1) Calorific power of the fuel.
- (2) Elementary analysis of the fuel and ash.
- (3) Analysis of the gaseous currents.
- (4) Temperature determinations at the various portions of the furnace.

*Ultimate Analysis and Calorific Power of the Coal.*—These determinations are made on representative samples of the fuel, the sampling to be done with great care, as very often the large pieces of coal have a different composition from the fine.

<sup>1</sup> It is by this method that we have made the test on a glass tank furnace, the results of which have been published in the *Annales des Mines*. The test was carried out for 36 hours, during which the weights of the coal and water used were taken; we were able to arrive directly at a figure which had been omitted in the chemical analyses. The exact measurement of the water corresponding to the amount of steam injected in the producer may prove difficult. The exact determination of the coal used is also almost impossible for a short period on account of the variations in the level of the producers. It is for these various reasons that a 24- (or better, a 36-) hour test is required.

The coal burned in our test had the following composition:<sup>1</sup>

Carbon.....	82.50%
Hydrogen.....	5.00
Nitrogen.....	1.20
Oxygen.....	6.00
Ash.....	4.10
Hygroscopic water.....	1.20
Total.....	100.00%
Calorific Power.....	8210 calories.

As the combustion of the coal is always incomplete, it is necessary to weigh the amount of ash produced, to sample it and to make carbon and water determinations. It must not be forgotten that the ashes to be collected must come from the coal the sample of which has been taken. Thus, before the collecting of the ash is begun, sufficient time must be allowed for the fuel charged in the producer to have come down in the ash-pit as ashes. The time to be allowed depends evidently on the size of the producer and the method of running it.

In our test the figures for the coal consumption and ash production were the following:

Coal consumption (36 hours).....	14500 kg.
Ashes .....	3500 "

*Analysis of the Ashes:*

Water.....	28%
Carbon.....	40
Ash.....	32
Total.....	100%

The coal contained  $14500 \times 82.5 = 11960$  kg. of carbon.

The ashes contained  $3500 \times 40 = 1400$  kg. of carbon.

The carbon of the coal escaping combustion is then  $\frac{140}{1196}$  of the total carbon of the coal.

We may write the composition of the coal as follows:

Burned carbon.....	728
Unburned carbon.....	97
Hydrogen.....	50
Nitrogen.....	12
Oxygen.....	60
Ash.....	41
Hygroscopic water.....	12
Total.....	1000

<sup>1</sup> The figures here used are taken from experimental studies, however; they do not all come from one such test. We intend to give here a numerical example to be used as a reference for future tests. It is not an actual furnace test.

The calorific power is to be decreased by the heat of combustion of the carbon unburned, which is equal to

$$\frac{97 \times 97.6}{12} = 788 \text{ calories}^1.$$

Calorific power of coal =  $8210 - 788 = 7422$  calories; calorific power per burned molecule (12 grams) of carbon of the coal:

$$\frac{7422 \times 12}{728} = 122.35 \text{ calories.}$$

Thus, the combustion of one molecule (12 grams) of carbon of the fuel will correspond to a liberation of 122.35 calories, coming from both the carbon and the hydrogen of the fuel. It is useful to thus compare to the burned molecule of carbon not only the total available heat, but also all the quantities of heat reacting in the furnace and all the gas analyses. The carbon is introduced in the furnace only by the combustion of the fuel (if we neglect the atmospheric carbon dioxide), so it is this element which can best serve as a unit of comparison.<sup>2</sup> The determination of the carbon in a gas will allow the estimation of the weight of the fuel corresponding to a given volume of the gas, and thereby the calculation of the ratio of the calorific power of the gas to the total available calorific power of the fuel; also, since we have used the thermal capacities per molecular volume, it is, then, the molecule which is most convenient to use.

*Gas Analyses.*—Two analyses are to be made—that of the producer-gas and of the waste products.

The samples taken must represent a fair average, and their multiplication can but be beneficial to accuracy. The waste products are to be collected at corresponding times of two periods of inversion; if the inversions are made every half-hour, the sampling will be made hourly. The sampling of the producer-gas will depend on the charging, as the composition of the gas depends

<sup>1</sup> A loss representing  $\frac{788 \times 100}{8210} = 9.60\%$  of the total available calories.

<sup>2</sup> If carbonaceous matter is charged in the hearth, as in glass or cement furnaces, it is evidently necessary to make allowance for this extra supply of carbon by following the method used in the case of the ashes of the producers.

on the time elapsed since the last charge, and the hydrocarbons are in larger amount soon after the charging. The sampling should then cover the time of a full cycle of a charging of the producers. The collecting tube should evidently be placed on the flue common to all the producers carrying the gas to the furnace, and not located on the flue of a single producer.

The analyses thus made in our test are as follows:

#### VOLUMETRIC ANALYSIS OF THE PRODUCER-GAS.

CO <sub>2</sub> .....	6.10%
CO.....	20.30
H <sub>2</sub> .....	13.20
CH <sub>4</sub> .....	2.70
N <sub>2</sub> .....	57.70
Total.....	100.00%
Water vapor.....	2.50%

The gas composition is to be compared with the molecule of carbon, the molecular volume is taken as the unit of volume in all the calculations that follow.

The figures for the carbon dioxide, carbon monoxide and methane correspond to a number of carbon molecules equal to their volume. Therefore the 100 volumes of dry gas or the 102.5 volumes of wet gas correspond to a number of burned carbon molecules:

$$6.1 + 20.3 + 2.7 = 29.1 \text{ molecules} \\ \text{CO}_2 \quad \text{CO} \quad \text{CH}_4$$

each molecule having liberated 122.35 calories.

#### VOLUMETRIC ANALYSIS OF THE PRODUCTS OF COMBUSTION.

CO <sub>2</sub> .....	14.30%	
N <sub>2</sub> .....	84.00	
O <sub>2</sub> .....	1.70	
Total.....	100.00%	
Water vapor.....	8.70%	108.70%

In this case, the composition of the products of combustion corresponds to 14.3 molecules of burned carbon, each having also liberated 122.35 calories.

*Measure of the Temperatures.*—The temperatures should be taken at the following points: At the entrance of the producer-

gas in the recuperative chambers, and as near the inversion valves as possible.

We assume this temperature to be  $600^{\circ}$  at the admission ports in the furnace of both the air and gas. Several determinations must be made, since the temperature varies from the beginning of an inversion to its end. Even in furnaces with parallel counter-currents, where there are a number of ports (as is the case in muffle furnaces for zinc distillation or for the manufacture of illuminating gas, and also in glass tank furnaces) the temperatures are not always uniform, and it is well to take readings at several ports. In this measurement it is absolutely necessary to introduce the pyrometric cane well inside the ports, so that the thermo-couple junction is well in the outgoing gas current. It must be far enough inside to be protected against the heat of the hearth. The cane must be kept in position until the needle of the galvanometer has come to rest, indicating that an equilibrium of temperature has been reached.

We have assumed these temperatures to be  $1200^{\circ}$  for both the air and gas.

In the hearth, it is well to make several determinations, as far as possible during the time allotted between two inversions.

We assume this temperature to be  $1500^{\circ}$ .

The temperatures at the base of the stack must be taken at frequent intervals and as close to the inversion valves as practicable. The cane is placed in the flue collecting the waste products issuing from both chambers, and an average temperature of the two currents is thus obtained. Great care is to be taken in this determination; to avoid error resulting from cold air rushing along the sides of the pipe on account of the stack draught, the cane should be thoroughly luted in.

It is seen that often a large number of temperatures are to be taken in a very limited time, the usual length of an inversion period being but 20 to 30 minutes. It has been found useful to place in position one thermo-couple at the gas flue, one at the stack, and a third one for the temperature determinations in the ports and hearth. The three couples are placed in electrical connection with the galvanometer by means of a switch-board, and it is thus an easy

matter to make a large number of determinations in a comparatively short time.

The same method is to be followed in taking gas samples; as many samples as possible should be taken in order to obtain a representative average.

The man in charge of the test has all he can do to attend to the pyrometric measurements, so he should have helpers on whom he can rely to take the necessary gas samples.

We assume the temperature of the products of combustion to be 400°.

It cannot be insisted upon too strongly that great care must be exercised if accurate results are to be obtained.<sup>1</sup>

#### CALCULATION OF THE EFFICIENCY OF THE FURNACE.

We have 122.3 calories as the total available number of calories per burned molecule of carbon. We will find the total heat carried by the gas as it leaves the producer at 600°, for a volume of gas corresponding to one molecule (12 grams) of burned carbon.

The percentage of the calories lost in the gas producer can be obtained at once:

CALCULATION OF THE CALORIFIC POWER OF PRODUCER GAS AT 600°

Gas	%	Sensible Heat at 600°		Latent	Heat
		Per Molecular Volume	In the Gas	Per Molecular Volume	In the Gas
CO <sub>2</sub> .....	6.10	6.44	39.28		
CO.....	20.30	4.31	87.50	68.2	1384.5
H <sub>2</sub> .....	13.20	4.31	56.90	58.2	768.3
CH <sub>4</sub> .....	2.70	8.02	21.65	195.2	527.0
N <sub>2</sub> .....	57.70	4.31	248.69		
H <sub>2</sub> O.....	2.50	5.87	14.67		
		468.69		2679.8	
Total heat		3148.5 calories			
Per molecule of burned carbon		$\frac{3148.5}{29.1} = 108.2$ calories			

<sup>1</sup> In the case of furnaces with parallel counter-current recuperation it is well to test the leakage of air through cracks and breaks in the recuperators by taking samples of the waste products as they leave the hearth, before they enter the recuperator, and to do the same thing in the flue leading to the stack. It has come within the experience of the writer that a counter-current recuperative furnace appeared to give a good efficiency owing to a low stack temperature, due merely to considerable air leaks, which lowered the temperature of the waste products on their way to the stack.—Translator.



$$\frac{122.35 - 108.2}{122.35} = \frac{14.15}{122.35} = 11.50\%$$

This represents the calories lost by radiation, convection and by the premature combustion of the carbon to carbon dioxide.<sup>1</sup>

We will now calculate the heat utilized in the hearth, by finding first the total calories brought by the air and gas at the temperature of 1200°, and then the total heat carried away at 1500° by the products of combustion.

The calorific power of the gas at 1200° is calculated exactly in the same manner as has been shown for the gas at 600°. It was found to be 3689.41 calories, or, per molecule of burned carbon:

$$\frac{3689.41}{29.1} = 126.79 \text{ calories.}$$

*Volume of Air Injected in the Chambers.*—This volume, taking into account the excess of air represented by the free oxygen, is derived from the analysis of the gas and that of the waste products.

20.3 volumes of CO require	10.15 volumes O <sub>2</sub>	+ 38.65 of N <sub>2</sub>
13.2 " " H <sub>2</sub> "	6.60 "	+ 25.13
2.7 " " CH <sub>4</sub> "	5.40 "	+ 20.56
Excess of air.....	3.46 "	13.17
Total volume of air.....	25.61	97.51

123.12

The sensible heat brought by the air at 1200° is 1114.2 calories, or, per molecule of burned carbon,  $\frac{1114.2}{29.1} = 38.29$  calories.

Total calorific power of the gas and air:

$$3689.41 + 1114.2 = 4803.61 \text{ calories.}$$

$$\text{Per molecule of burned carbon } \frac{4803.61}{29.1} = 165.08,$$

a number greatly superior to that of the fuel; the difference be-

<sup>1</sup> The true loss in the producer (which, however, has no bearing on the efficiency of the other furnace organs) is: 9.60 + 11.50 = 21.10%. To this should be added the coal burned on the boiler grate to generate the steam required for the injector when used. A total loss of 25 to 30% can be considered a fair figure as the total absolute loss in converting the coal into gas.—*Translator.*

tween this total calorific power and that of the gas at its leaving the producer is due to recuperation.

$$\text{Recuperative Effect} = \frac{165.08 - 108.2}{122.35} = \frac{56.88}{122.35} = 46.50\%$$

The 56.88 calories are recovered from the products of combustion that otherwise would have carried them to the atmosphere.

*Calories Contained in the Products of Combustion at 1500°.*—This quantity of heat is found as follows:

Gas	%	Thermal Capacities per Molecular Volume at 1500°	Total
CO <sub>2</sub> .....	14.3	21.0	300.3
O <sub>2</sub> .....	1.7	11.50	985.55
N <sub>2</sub> .....	84.0	18.50	160.95
H <sub>2</sub> O.....	8.7		
Total.....			1446.8 calories.

$$\text{Per molecule of burned carbon} \frac{1446.8}{14.3} = 101.18 \text{ calories.}$$

According to our definition of Heat Utilized, the difference between the heat brought in the hearth and the heat carried away by the waste products gives the amount of the heat utilized:

$$165.08 - 101.18 = 63.9 \text{ calories.}$$

$$\text{Percentage of the Heat Utilized} = \frac{63.9}{122.35} = 54.23\%.$$

Calories carried away by the waste products into the atmosphere:

Gas	%	Thermal Capacities per Molecular Volume at 400°	Total
CO <sub>2</sub> .....	14.3	3.99	57.06
O <sub>2</sub> .....	1.7	2.22	241.67
N <sub>2</sub> .....	84.0	3.69	32.10
H <sub>2</sub> O.....	8.7		
			330.83

Per molecule of burned carbon  $\frac{330.83}{14.3} = 23.13$  calories.

Percentage of heat lost =  $\frac{23.13}{122.35} = 18.91\%$ .

We have, then, the following heat balance-sheet:

Heat lost in gas-producer.....	11.50%
Heat utilized (*U*).....	52.23
Heat lost in the waste products.....	18.91
Heat lost by cooling of the recuperative chambers (by difference).....	17.36
Total.....	100.00%

## CHAPTER X.

### DISCUSSION OF THE THEORY OF HEAT RECUPERATION IN THE LIGHT OF EXPERIMENTAL DATA—GENERAL CONCLUSIONS AND CLASSIFICATION.

The general study we have given shows that there may be a marked difference between the theoretical and the actual efficiencies. Thus our double recuperative furnaces fired with mixed gas had an efficiency of 52.23% against a theoretical efficiency of 85%.

The calories lost by radiation in the producer and in the chambers; the premature combustion of the carbon in the producer, and in general all the practical conditions (in contradiction to our theoretical study), had a marked influence on the efficiency.

In order to preserve the correctness and exactness of the theory, as well as of the conclusions made therefrom, we must again take up our hypotheses and show that, while modifying the absolute values of the figures of the calculated efficiencies, they have little bearing on the relative figures; at least, they cannot change the order of the classification.

Before taking up the general discussion, let us remark that the maximum efficiencies given in Table 11 are limits toward which the efficiencies of the furnaces will tend with the advance in furnace construction.

If the classification is not mathematically correct today, it will tend to become more and more so in the future; on this account, alone, the classification is worthy of interest.

We will show, however, that the order of the classification cannot be changed, with the understanding that the furnaces be built under similar conditions as regards the grouping of the various organs of the apparatus and of the cooling surfaces.<sup>1</sup>

<sup>1</sup> It is evident that two furnaces built along widely different lines may from this very reason show anomalous efficiencies. Thus, a well-grouped furnace with single recuperation may have a better efficiency than a double recuperative furnace with its chambers in-

Our first hypothesis<sup>2</sup>—*complete fuel gasification in carbon monoxide*—is far from being realized. There is almost always about 5% of CO<sub>2</sub>, with 20 to 22% of CO. This premature combustion of the carbon lowers the efficiency by the increase it brings in the primary air and in the gas temperature; both results are harmful to good recuperation. Neglecting the slightly increased radiation in the producer resulting from the higher gas temperature, it is easily seen that this premature combustion cannot modify the classification.

It is permissible, in fact, to consider furnaces fired with gases containing 5% of carbon dioxide as one-fifth direct-fired furnaces, and the remaining four-fifths as gas-fired furnaces with the efficiencies we have given for the two systems. The differences between the efficiencies of the various systems will be modified in the ratio 4 : 5 without altering their classified order.

The second hypothesis concerns *the invariableness of the ruling temperature throughout the furnace—in the producer, the hearth, etc.*

In furnaces working continuously, with Siemens inversion, the temperature of the chambers will oscillate about 100° between the beginning and the end of an inversion, according to the time occurring between two consecutive inversions. These differences affect only the sensible heat of the gases, and are small enough to be negligible. With parallel counter-current furnaces the invariableness is maintained.

The third hypothesis, in which we omit *the cooling of the gas-producer*, has a greater importance. The heat loss has been found to be 11.50%.

For the same method of gasification and the same type of gas-producers, and operated in a like manner, this thermal loss will be a constant which will not affect our classification. If the change is made from Siemens gas to mixed gas, the cooling will be less in the second case than in the first, and it will give a further advantage to the mixed gas. This will serve only to increase the difference sufficiently protected, and not properly grouped for the prevention of radiation losses. It will also be possible to have a better efficiency with a New Siemens furnace than with a furnace with double recuperation with mixed gas, if the cooling surfaces of the latter are considerable. This would not, in any case, invalidate our theory or modify our conclusions.

<sup>2</sup> See page 67 for the hypotheses, which have been taken as the basis of the general theory.

ence indicated by the theory in the better recuperation and in the accentuation of the classification.

The two hypotheses, which are also the least in accord with practice, remain—that of *the neglect of the cooling of the recuperative chambers*, and that which admits as possible *a perfect exchange of calories between the cold and the hot gases*.

It has been found in our experimental test that the cooling of the chambers may reach 20%, and the gap between the temperatures of the waste products and the recuperated gases may be 300° for a temperature of 1500°. Finally, in spite of this difference, which reduces more than one-fifth the efficiency of the recuperation, the recuperated heat may be from 40 to 50%.

These figures have weight and should be considered. In order to appreciate their influence on the efficiency we may note that both result from the nature of the recuperative organs, and if we show besides that they are functions of recuperation itself—that is, of the calories won from the waste products—we will have shown that their effect on the efficiency is proportional to the various efficiencies themselves, and therefore cannot modify the classification.

The volume, or more accurately the useful surfaces, of the recuperative chambers should be calculated to suit the exchange of the calories to be effected, according to the specific heats of the recuperating refractory bricks. These chambers will be the larger, and thereby their radiation will be the greater, the more efficient the recuperation. There will then be a certain relation between the loss by the cooling of the chambers and the recuperated heat.

The difference between the final temperatures of the recuperating gases and the initial temperature of the waste products will have the same relative importance. This loss is incurred only by the gases taking an active part in the recuperation, and the loss of calories resulting therefrom will be the greater the larger the mass of gases flowing through the recuperators, and therefore it increases with the bettering of the efficiency.

This proportionality is exact if air is the only recuperating gas. In the case of producer-gas recuperation, owing to its high initial temperature, the radiation loss and the recuperative loss will in-

crease with the initial temperature of the gas. It follows that the mixed gas will again be more efficient than the gas of any other system. Our classification is thus made only more marked in its divisions.

We have finally to appreciate the change that may be brought in the classification by the nature of the fuel. We made the hypothesis that the fuel was an ashless coke, containing nothing but carbon. It is evident that we might have repeated our various calculations with different fuels, hydrogen, methane, etc.; but these substances exist only in small quantities in the coals, and such calculations would present only an academic interest. It will be sufficient to note that the presence of these bodies, which enrich in so marked a degree the various fuels, will counteract in a way the premature combustion in the producer, and therefore will tend to bring closer the actual and the theoretical classification without changing the relative positions.

It is permissible now to affirm that the classification of the various systems of furnaces, based on the calculated theoretical efficiencies, is in accordance with practice, and can serve as a sure guide in the study and selection of the type of furnace to be used for a given set of conditions.

Doubtless, furnaces may be found in practice that form an apparent exception to these laws; for example, a poorly designed furnace with double recuperation may consume more coal for a given work than a good single recuperative furnace; but from such a fact it is impossible, and certainly not legitimate, to draw any conclusion asserting the superiority of the second system over the first.

The only objections worthy of consideration are those based on a complete heat balance-sheet, which alone can allow a logical criticism of a heating system. We do not believe that up to date there has been a sufficient number of such tests made to control experimentally the theory of heat recuperation. To multiply such tests is vital to the progress of the art. They would constitute an ensemble of experimental facts, which, taken together with the undeniable theoretical figures, would make a proper judgment of the furnace question possible.

In the absence of experimental data, the safer guide will be to rely on the theoretical efficiencies so much the more since the discussion has only confirmed their value.

We believe that we may safely conclude:

(1) In maintaining a new practical value of the table of efficiencies, taken with the reservation we have given.

(2) In asserting once more the two results that appear to us of the greatest interest: the actual superiority of furnaces with double recuperation with mixed gas in the case of high temperatures; the importance of improvement of gas-producers for the injection of highly heated primary air, which alone will allow of a simpler recuperating apparatus with an efficiency higher than any in practical use today.

The first of these conclusions concerns the present condition of the art. The second is an indication for the future which we hope may serve to show the desiderata yet to be realized. Though the theory of the maximum efficiency is established in a definite and permanent manner, the industrial efficiency is still subject to such variations that the classification given in our study may be modified in the future according to the never-ceasing progress in the science of heating.<sup>1</sup>

<sup>1</sup> We insist, forcibly, on the necessity of complete heat balance-sheets, with records of gas analyses and temperatures. Furnace builders seldom pay any attention to them. The only datum that interests them is the ratio of the weight of fuel burned to that of the metal treated. This, evidently, is of great importance to works managers, but we maintain that it is insufficient to estimate the value of a furnace, since it is not given together with the length of the operation and the dimensions of the furnaces.



**PART II**

**METHODS OF CONTROL**

**PYROMETRY. GAS ANALYSIS**

**BY**

**A. L. J. QUENEAU**

---

**CALORIMETRY. ELEMENTARY**

**FUEL ANALYSIS**

**BY**

**MYRICK N. BOLLES**





## PART II.

---

### CONSIDERATION OF PRACTICAL PROBLEMS.

#### CHAPTER XI.

##### PYROMETRY.

From the preceding chapters we have seen that it is necessary, in making furnace tests, to be able to measure rapidly and accurately the temperatures in the various parts of the furnaces. The instrument to be selected for the work should therefore be portable, accurate, easy of handling, and should allow the reading of temperatures at widely distant points.

Of the many types of instruments the Le Chatelier thermo-electric pyrometer offers all of the mentioned desiderata. The thermo-electric instrument being small can be introduced into any part of the furnaces, and since a few seconds are sufficient for the establishing of an equilibrium of temperatures, it can serve to measure temperatures close to  $1780^{\circ}\text{C.}$ , the melting point of pure platinum, without endangering the life of the wires. On account of the electric current generated, any number of thermo-couples can be connected with a single galvanometer by means of a switch-board; for the same reason the instrument may be placed at any convenient distance from the furnace.

The Le Chatelier pyrometer is thoroughly reliable, if ordinary care is taken of the wires. However, in order to be successful with the instrument, its limitations should always be borne in mind; these are due entirely to the nature of the metals forming the couple. Practically the same care that is to be taken with platinum ware is required with the wires of the thermo-couples. Platinum is readily attacked by the vapors of volatile metals; silver, zinc, an-

timony and copper are especially to be dreaded. In a reducing atmosphere, silicates and phosphates are also objectionable.

In spite of the most thorough protection, platinum and its alloys suffer physical alterations, resulting in great brittleness, by mere continuous heating to temperatures above  $1000^{\circ}$ . Several types of galvanometers are made, giving good satisfaction, especially

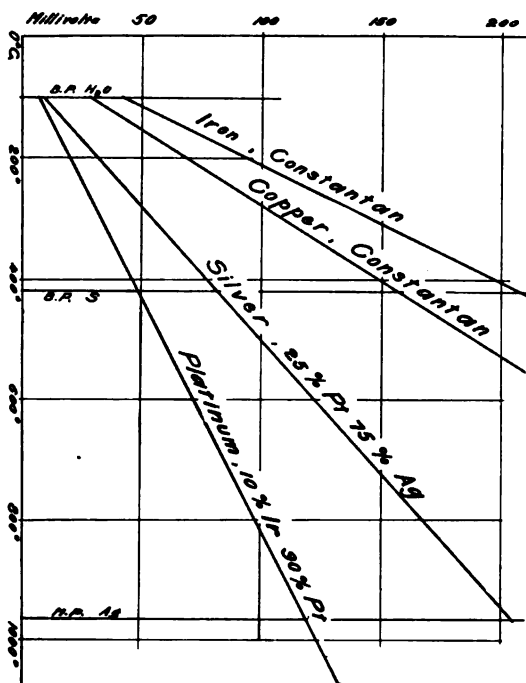


FIG. 43.—E. M. F. CURVES OF DIFFERENT THERMO-COUPLES.

the Siemens and Halske, the Pellin, and that of the Cambridge Scientific Instrument Company.

The Le Chatelier pyrometer, though very widely used, has not yet received the universal approval that it deserves, probably from lack of knowledge as to its practicality.

For the same reason great stress has been unduly placed on the importance of the composition of the thermo-couples. The truth

is that there exists a large number of thermo-couples, each with its own field, that give good satisfaction. With platinum couples the question of purity is important, especially with the platinum wire, as a slight amount of impurity will cut down the electromotive force much more quickly than a corresponding amount in an alloy wire.

Among the couples used by the writer are the following:

- (1) Pure platinum and an alloy of 10% rhodium and 90% platinum.
- (2) Pure platinum and an alloy of 10% iridium and 90% platinum.
- (3) Pure silver and an alloy of 25% nickel and 75% copper (constantan).
- (4) Pure copper and constantan.
- (5) Pure silver and an alloy of 25% platinum and 75% silver.
- (6) Pure iridium and an alloy of 10% ruthenium and 90% iridium.

Iridium and rhodium give equally good results, with the material advantage for the iridium alloy that it is much cheaper, that it can be readily obtained from any platinum refiner in sufficient purity for industrial work, and that it has a higher E. M. F. at temperatures above 1000° C. than the rhodium alloy.

The ruthenium-iridium couple is useful only for high temperature measurements, those above the melting point of platinum. It is extremely brittle, but can be used up to 2100° C.

The silver and platinum-silver couple is very convenient for temperatures up to the melting point of silver (962° C.). This couple costs much less than the platinum element, and has nearly double its E. M. F.

The constantan couples are very useful for low temperatures from 0° C. to 300° C. They have very high E. M. F., with the further advantage of being cheap.

It follows that we have at hand a number of couples from which we may select the one most suited to the work to be performed. The main point to be remembered is that, owing to the necessary standardization, we may use any couple giving concordant results.

It is only required to know the law of the E. M. F.'s. to be able to use the couple with accuracy.

*Principle of the Thermo-Electric Pyrometer.*—Whenever two metals in contact are heated, an electric current is generated which is a function of the temperature. In a circuit composed of a number of metals, the resulting current is equal to the algebraic sum of the various component currents.

The E. M. F. of a couple is not altered when one or several metals are inserted between the metals of the couple. It follows that any metal can be used as solder; from this principle is derived the wire method of standardization of Holborn and Day (see p. 159).

On account of the importance a minute quantity of impurity plays in the pure metal used in the thermo-couple, it follows that no two couples made from different ingots have exactly the same E. M. F. It is thus a useless refinement to provide the galvanometer with a temperature scale; the use of that scale is limited to the use of the couple sold with the instrument, and does not entirely suffice for that, since the couple will change its E. M. F. after hard usage, requiring restandardization.

When couples are to be used in large number, it is good policy to order a length of wire made from a single ingot, long enough for one year's supply. The wire lot should be sampled at both ends and at the middle, and all samples standardized. If all the samples give the same results, the wire lot may be considered as homogeneous, and no further standardization is necessary.

For testing furnaces of temperatures ranging to 1600° C. and above, the iridio-platinum is to be used. Before making the couples, the wires should be annealed to a temperature equal to, or even higher than, that at which they will be exposed. The annealing is best done by an electric current, though it can also be done with the oxygen lamp.

The junction should be made by twisting the wires together and melting the twist carefully with an oxygen blast until a globule is formed. Care should be taken to avoid twisting and kinking the wires after the annealing. Even in perfectly homogeneous metals, a distorted section will, when heated, give rise to an electric current,

which of course will affect, in greater or lesser measure, the readings of the galvanometer.

It must be borne in mind that the wires will not stand heating over  $1000^{\circ}\text{C}$ . for more than a few hours without serious change in their physical conditions, even with the best of protection against the contact of silicious material and surrounded by an oxidizing atmosphere. The writer has had wires in spelter furnaces for 48 hours continuously, the temperature reaching  $1500^{\circ}\text{C}$ ., but they gave correct readings as long as they were left undisturbed; the least jar was sufficient, on account of the induced extreme brittleness, to make them fall to pieces. The effect seems in this instance to have been purely physical, since the couples gave correct deflection to the last. This was ascertained by having a fresh standard couple inserted at the time of the breaking down. The brittleness is specially marked with the platinum alloys; the pure platinum wire will still be in fair condition when the platinum-iridium wire has completely failed.

With proper care the Le Chatelier thermo-couple can be used for a large number of tests. With the body of the couple properly protected, the length of the couple exposed need be only 3 cm. In such a case, the thermo-couple introduced into a furnace, say at  $1600^{\circ}\text{C}$ ., will reach a condition of equilibrium in about five seconds, often in three; it is then possible to measure very high temperatures without danger of losing the wires, or of injuring them.

A common false economy, in the case of the Le Chatelier thermo-couples, is to make use of wires of too small a diameter; usually the wires sold are 0.6 mm. in diameter. One millimeter is a better diameter, the increased cost being fully offset by the much greater resistance of the wires to corrosion and mechanical rupture.

The cost of the Le Chatelier unstandardized iridio-platinum couples is about 75c. a gram; the scrap wire can be sold for about 60c<sup>1</sup>.

If constantan or silver wires are used, the cost is nominal. The writer knows of over one hundred couples put in furnaces, several years ago, for continuous record of temperatures below  $1000^{\circ}\text{C}$ ., which are as good today as the first day they were put in place.

<sup>1</sup> Varying with the metal market.



FIG. 44.—PYROMETRIC CANE FOR THE PROTECTION OF THE WIRES OF LE CHATELIER THERMO-ELECTRIC PYROMETER.



Outside of the advantages that may result from the knowledge of the temperatures, the use of registering pyrometers always tends to insure regularity of operations. The men know very soon that there is in operation an instrument that records automatically the charging, tapping, reversing of valves, etc., and the moral effect is conducive to good work; very soon they will recognize in the instrument a valuable help in the correct operation of the furnaces. Once the standard basis of good work has been established in relation to some automatically recorded factor, it may be good policy in some cases to give a premium for increased efficiency.

In blast furnaces, it is good practice to have recording pyrometers on the bustle-pipe and on the down-comer (and on the equalizer if one is used), besides having a direct-reading instrument connected with the various ovens or stoves. The couple on the down-comer gives valuable information as to the running of the furnace, the position of the stock line, the time of charging, etc.

The continuous record of the temperature of the waste gases at their leaving the chambers may also give interesting information regarding the regularity of operation of regenerative furnaces.

Another use of the pyrometer, outside of determining exact furnace temperature, is as a means of control of operations in the furnace, especially in connection with a recording galvanometer. If a fixed temperature relation exists between the walls of the furnace and those of the hearth, the thermo-couple will give just as useful information, placed in the wall, flush with the inner face, as if it were in the center of the hearth. The relation between the two points is easily ascertained by inserting a thermo-couple in the selected part of the hearth and comparing the readings given by the galvanometer when connected with either of the couples. As an instance of this method the writer installed thermo-couples in the walls of a number of blende-roasting kilns, the end of the firebrick protecting tube being flush with the wall of the kiln (Fig. 51).

If care is taken to have a complete spare thermo-couple always at hand, it is a small matter to replace an injured instrument; all there is to do is to make the lead connections. The thermo-couple wires should always be soldered to the copper leads, and never

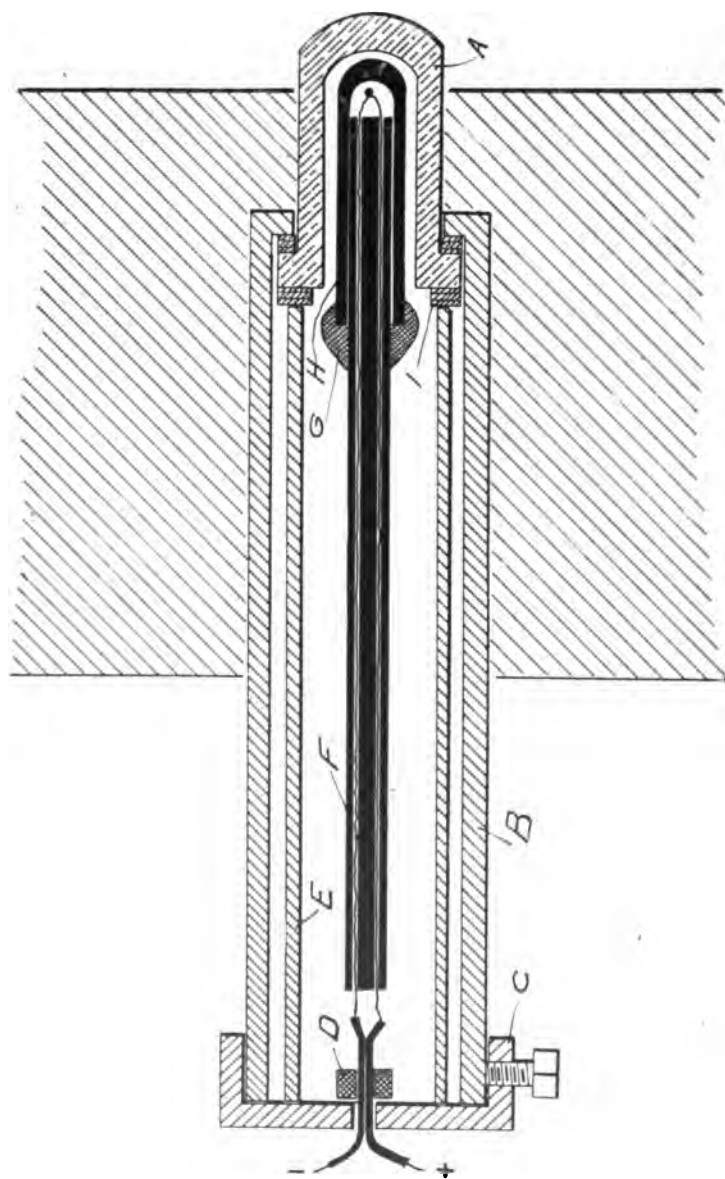


FIG. 45.—APPARATUS FOR THE PROTECTION OF THE THERMO-COUPLE IN ROASTING KILN.

connected by merely twisting them together. The galvanometer may be located at any convenient place—a mile removed if necessary. Care must always be taken, in order to insure accuracy, to standardize the couples with the same length of wire as that used for the work. The necessary length of the copper wires may be actually used, or an equivalent resistance.

It is to be remembered that the thermo-electric current generated is proportional, not to the actual temperature of the thermojunction, but to the difference in temperature between the hot and the cold junctions. Care, therefore, should be taken to protect the connections of the thermocouples with the copper leads (the cold junction) from undue heating; in case this protection is not possible, it becomes imperative to use a water-cooled end. This, however, is seldom necessary, as it is usually sufficient to make correction for the temperature of the ends, which is about that of the surrounding atmosphere.<sup>1</sup>

#### STANDARDIZATION.

In order to find the temperature corresponding to a given deflection in millivolts of the galvanometer, it is necessary to find the number of millivolts corresponding to known temperatures. Such temperatures are given by the melting and boiling points of chemical elements or definite chemical compounds. Mathematically speaking, with the pure platinum and iridio- or rhodio-platinum couples, it is sufficient to determine two points; by means of a logarithmic formula it becomes possible to find any other temperature corresponding to a given deflection.<sup>2</sup> However, both for rapidity and safety it is better in industrial work to use the graphic method. If, on a sheet of coördinate paper, the temperatures are plotted on one axis, the millivolts on the other, the intersections of the ordinates and abscissæ will give a series of points lying on a curve characteristic of the couple.

The fixed points to be selected are the following:

<sup>1</sup> The mercury rheostat of William Henry Bristol affords an ingenious and effective method of compensating this source of error: it is formed of a coil of wire sealed in a thermometer, the mercury of which cuts off a greater or lesser length of the resistance with the change in the ambient temperature.

<sup>2</sup> S. W. Holman, *Proc. Am. Academy Arts and Sciences*, XXXI (N. S. XXIII), p. 234.

Boiling points of	Water,	H <sub>2</sub> O.....	100° C.
	Naphthaline,	C <sub>10</sub> H <sub>8</sub> .....	218°
	Sulphur,	S.....	445°
Freezing points of	Zinc,	Zn.....	419°
	Aluminum,	Al.....	655°
	Silver,	Ag.....	962°
	Gold,	Au.....	1065°
	Platinum,	Pt.....	1780°

For determining the boiling points of water, use naphthaline and sulphur, the apparatus of Barus (illustrated in Fig. 52).

The bulb test-tube is inserted in a muff of plaster of paris, after having been filled about one-third its lower length with the substance to be used; heat is carefully applied until ebullition has begun. Care should be taken, especially with the sulphur and the naphthaline, to keep the level of the vapors somewhat below the mouth of the tube, otherwise the vapors will catch fire. For these determinations it is not usually necessary to have any insulation around the wires in the test-tube; it is sufficient to spread them apart so that they will not touch each other and thereby short-circuit the current. From the test-tube to the galvanometer it may or may not be necessary to protect them. The wires of the thermo-couple may be led directly to the galvanometer or they may be connected to copper leads. The junction of the copper wires and of the couple wires may be inserted in a large-necked bottle containing water, in order to keep the cold junction at a uniform temperature; in most instances, however, it is a useless refinement, since there are quite a number of other junctions, namely, that of the copper leads with the binding-posts of the galvanometers, and the different junctions in the body of the galvanometer, made in most instances of different metals. It is as well for all practical work to connect the leads directly to the binding-posts of the galvanometers and to note the temperature of the room. The complete standardization of a couple can be done in about two hours, and in that interval of time it is seldom that the difference of temperature will be more than a few degrees; the reading of the thermometer will give the means of making the necessary connections. Care is to be taken to have the galvanometer sufficiently removed from the source of heat.

With the boiling points, the needle of the galvanometer will

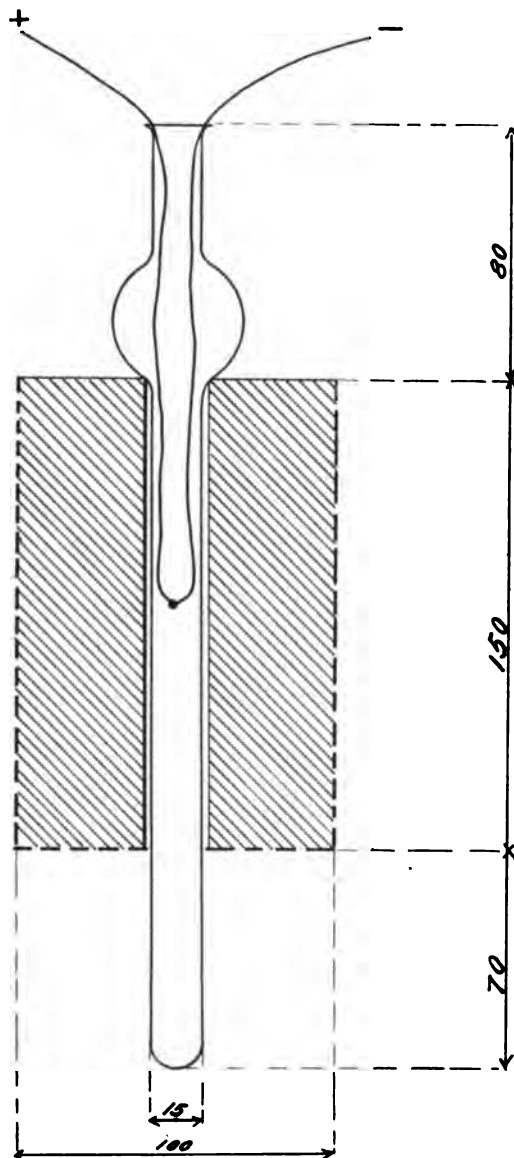


FIG. 46.—APPARATUS FOR THE DETERMINATION OF BOILING POINTS.

reach a stationary position when the thermo-couple junction has reached an equilibrium of temperature with the vapors. The junction should be placed well within the plaster muff, but not inside of the liquid. It is always well to allow the liquid to cool, and to re-heat it to the boiling point several times, in order to be certain of the results.

When couples other than that of the platinum group are standardized, it is well to protect the wires from the contact of the sulphur vapors; in such a case, a covering can be made of hard glass, as shown in Fig. 48.

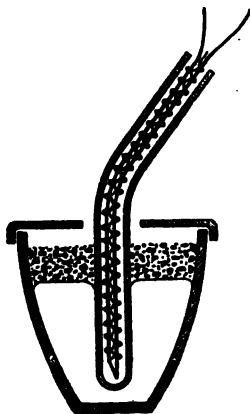


FIG. 47.—APPARATUS FOR THE DETERMINATION OF THE BOILING POINT OF ZINC. (FROM LE CHATELIER-BOUDOUARD-BURGESS' HIGH TEMPERATURE MEASUREMENTS.)

For the determination of the melting points or freezing points the wires should always be protected; the best covering is afforded by porcelain tubes, as shown in Fig. 49. About 35 to 50 grams of the substance to be used is taken and placed in a small crucible; the No. 00 graphite crucibles are well suited for that work. For zinc, aluminum, silver, and copper, the crucible method is to be preferred, while for the precious metals, gold and platinum, the wire method is the best; it is also well adapted to silver and aluminum.

*Crucible Method.*—The furnace to be used whenever possible is the electric-resistance furnace, the resistor being either nickel or platinum wire or platinum foil, according to Heraus' method. In Fig. 50 is illustrated such a furnace; the wires are either platinum or nickel. With platinum wires, pure nickel has been melted in a little over 30 minutes, starting with the furnace cold. The great advantage of the resistance furnace is that a perfectly uniform temperature can be obtained and maintained for any length of time, and that no reducing flames are present. For the wire method a tube furnace can be very well used. In Fig. 51 is given the design of a furnace that can be built at almost any works; it is comparatively cheap and highly efficient. The resistor can



FIG. 48.—FLETCHER FURNACE.

be made of nickel, platinum wire or ribbon. If an electric furnace is not to be had, use can be made of the Fletcher furnace, using either air or oxygen blast. If a Fletcher furnace cannot be procured, a simple and effective furnace is made, as shown in Fig. 49, by taking two crucibles fitting snugly one into the other. One or two tuyere holes are cut in the outside crucible and the blast is applied through the openings; the apparatus answers well for the melting of gold or copper.

When making determinations it is well to insert the porcelain tubes at the beginning of the operation before the flame is applied, so as to avoid the cracking of the tubes by too sudden a heating. The heating should be conducted slowly and continued until the

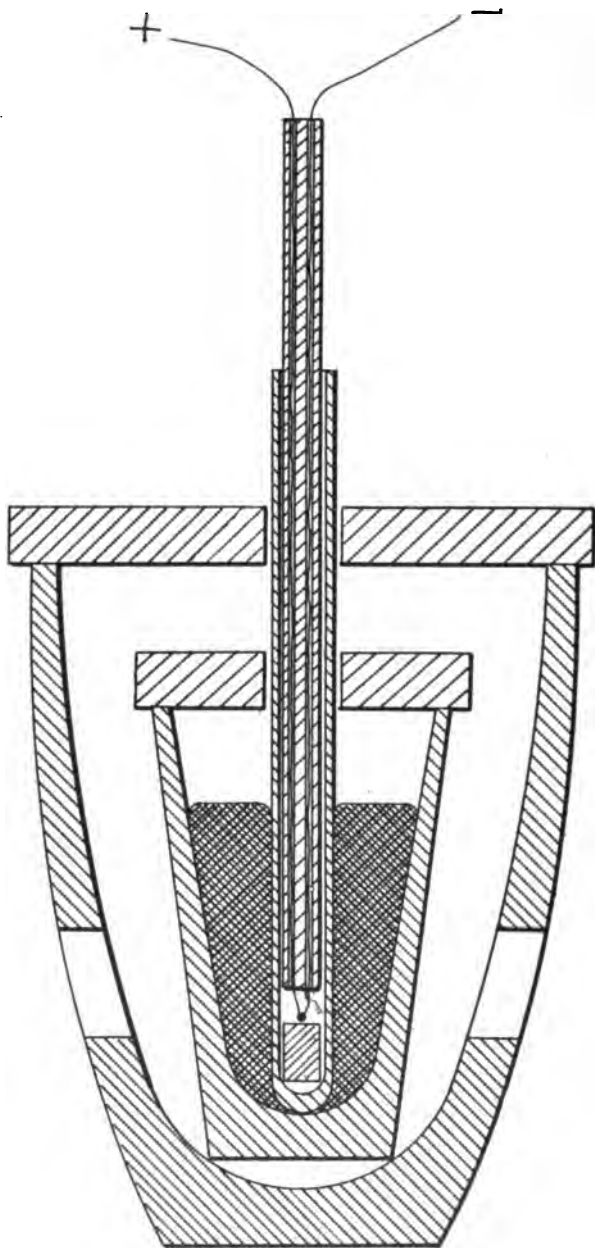


FIG. 49.—SIMPLE APPARATUS FOR THE DETERMINATION OF THE MELTING AND FREEZING POINTS OF METALS.



metal is melted; this can be ascertained either by direct observation by feeling the solid metal ingot with the porcelain tubes, or by the deflection given by the galvanometer. It is not necessary in the crucible method to watch for the melting point; once certain that the metal is fused, the heating is stopped, the furnace is allowed to cool slowly and regularly, and at the instant the mass has reached the freezing temperature, a well-marked stop is observed on the galvanometer needle. With proper care, and with gradual cooling, it is very easy to have the needle stationary for 30 seconds with a mass of 35 gr. It is always well to repeat the operation.

*Wire Method.*—The wire method allows the determination of the melting points of the precious metals with the use of only a very small weight of the same. A 20-mm. length of this wire is twisted and soldered at the end of the wires of the thermo-couple, in such a way as to form the thermo-junction. (See Fig. 51.) Care is to be taken that the wire is not under tension, otherwise the thermo-couple wires would break the softened wire some degrees before the true melting point. The thermo-couple is inserted in a suitable furnace, preferably an electric furnace, which is slowly heated to the required temperature. The needle of the galvanometer is abruptly released when the melting point is reached; the maximum reading corresponding to the sought temperature.

The determination of the melting point of platinum is conveniently made at the time of the fusing of the thermo-junction. A twist some 10 mm. in length is formed from the thermo-couple wires, and the flame of the oxygen blowpipe is made to play at the very end of the twist. The flame follows the bead of molten platinum in its travel toward the free wires; the fusion is stopped when the latter are bathed in the bead. The melting point corresponds to the steady maximum deflection. Care is to be taken that the flame does not come in contact with either wire—their thermal capacities being less than that of the bead, they would be quickly cut.

#### ELECTRIC FURNACES.

The electric furnaces suited to pyrometric work are limited to resistance furnaces or induction furnaces. Direct current being

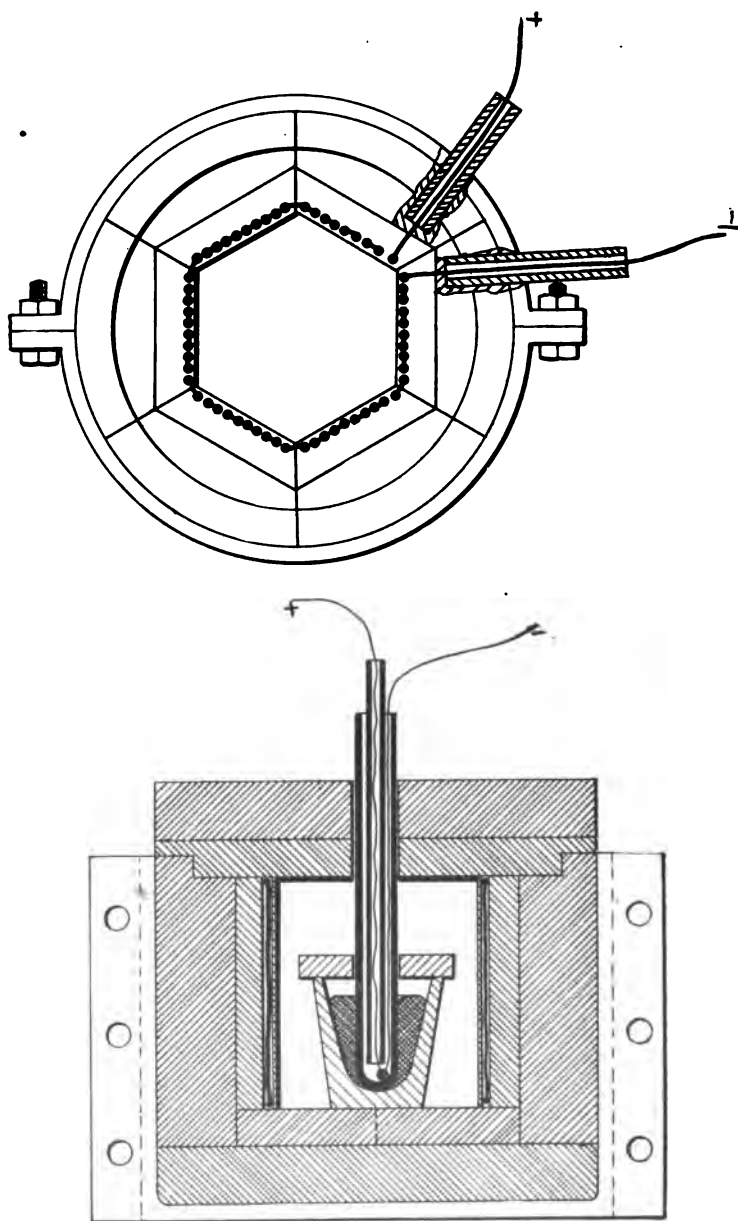


FIG. 50.—QUENEAU ELECTRIC RESISTANCE CRUCIBLE FURNACE.

most easily obtained, we will limit ourselves to the description of resistance furnaces.

The resistance for high-temperature work may be formed of carbonaceous material, metals and their alloys, and, according to the method of Nernst, of oxides of the rare earths. When the facility of construction, the cheapness of apparatus, the constancy of the resistance and the ease of getting the necessary materials are considered, it is apparent that the choice will rest with the metallic resisters. Not that they give in themselves perfect satisfaction, but if the furnaces are operated within the safe temperature limits, the metallic resisters will prove satisfactory. We are evidently limited to metals or alloys with high melting points and those not readily oxidized. Thus we cannot go outside of the platinum group of metals, although for temperatures below 500° C. it is possible to use nickel for considerable periods of time.

According to the discovery of Dr. Heraus, of Hanau, the most efficient form of metallic resistance is in the shape of thin foils; they afford a very large radiating surface with a small weight, an important consideration with a metal as expensive as platinum.

Broadly speaking, furnaces may be divided into crucibles and tube furnaces. A type of crucible furnace which has given good satisfaction is illustrated in Fig. 50. The furnace is enclosed in a cast-iron casing, inside of which is a first layer of plates enclosing in their turn an inner layer which form the hexagonal recess. On top and on the bottom the cavity is similarly completed with a double set of plates. The top, bottom and outside plates are made of good fireclay, mixed with the proper amount of firebrick sand, while the thin inner plates are made of magnesite, thoroughly calcined at a temperature higher than the highest temperature to be reached in the furnace. The calcined magnesite is mixed with a binder formed of a thick solution of dextrine, sodium silicate and some raw fireclay. The mold is provided with the necessary number of wires to furnish the passages for the metallic resister. The type illustrated has plates with an inner face of 51 mm. by 110 mm., each plate having 10 holes. The plates are wired separately and mounted in series.

By selecting the proper cross-section of wire, knowing the re-

sistance of the metal selected, it is possible to utilize the current at hand. It is always well to try the length of the wire selected in the open air; by sliding a movable binding-post it is possible to check accurately the calculations. The walls and bottom of the crucible chamber are made smooth by filling up all inequalities in

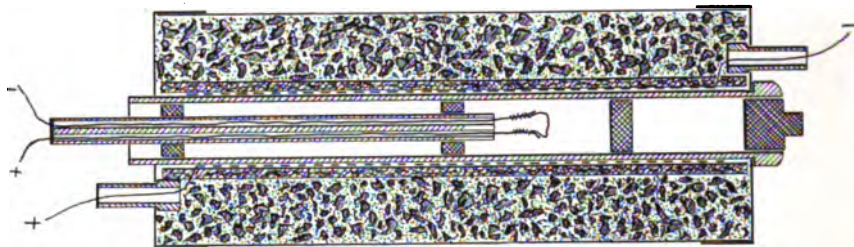


FIG. 51.—ELECTRIC RESISTANCE TUBE FURNACE, ILLUSTRATING THE WIRE METHOD.

the surfaces by what is known as asbestos cement (a mixture of shredded asbestos fibers and water-glass).

With such a furnace the fusion of pure nickel is readily obtained; however, it is better adapted for temperatures up to  $1300^{\circ}\text{C}$ . as a maximum. With a rheostat it is possible to maintain a temperature

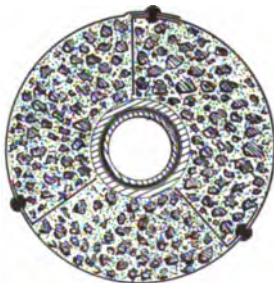


FIG. 51a.—CROSS-SECTION OF THE TUBE FURNACE.

constant to within a few degrees. The furnace was designed for the study of Stephan's law; it gave the radiation of a black body.

The same type of refractory bricks, with perforations close to one of the faces, forms a material well adapted to the making of hot plates for laboratory works. By modifying the design to suit

special conditions it is possible to use the plates for the not-air bath, sand plates, stills, combustion furnaces, etc.

A *tube furnace* is illustrated in Fig. 51. It is cheaply and easily built, the only expense being the cost of the metallic resister. The porcelain tubes which are commonly used as insulators in electrical wiring answer very well up to the highest temperatures obtainable with platinum wires. The wire, preferably rolled flat, or the Heraus foil, is wrapped along a helix of small pitch ( $\frac{1}{4}$  in.) as uniformly as possible. (By tracing a helix first in pencil on the white porcelain tubing, it is an easy matter to make an almost perfect laying.) The ends being fastened by means of strings, a



FIG. 52.—SIEMENS-HALSKE DIRECT-READING GALVANOMETER FOR LE CHATELIER THERMO-ELECTRIC PYROMETER.

jacket of asbestos cement is placed by hand over the wires and the cement allowed to dry. This drying operation may be effected more rapidly by connecting the ends of the wires with the poles of the source of electricity by means of a rheostat. The heating should be done very gradually until the jacket is sufficiently hardened. The tube is placed in the center of the sheet-iron body, as shown in Fig. 57, the space between the jacket and the sheet-iron walls being packed tight with a mixture of quicklime and charcoal, broken to hazelnut size. The lime will prevent the oxidation of the charcoal, and the mixture forms a good heat insulator. The tube is plugged by flat cylinders of graphite, cut from graphite brushes.

## PYROMETRIC GALVANOMETERS.

The instrument should be "deadbeat"; that is, the oscillations of the needle should stop dead after a few vibrations. If the instrument is to be located permanently, the support should be made of a concrete or brick pier with independent foundations, so as to have as little vibration as possible. If vibrations cannot be alto-

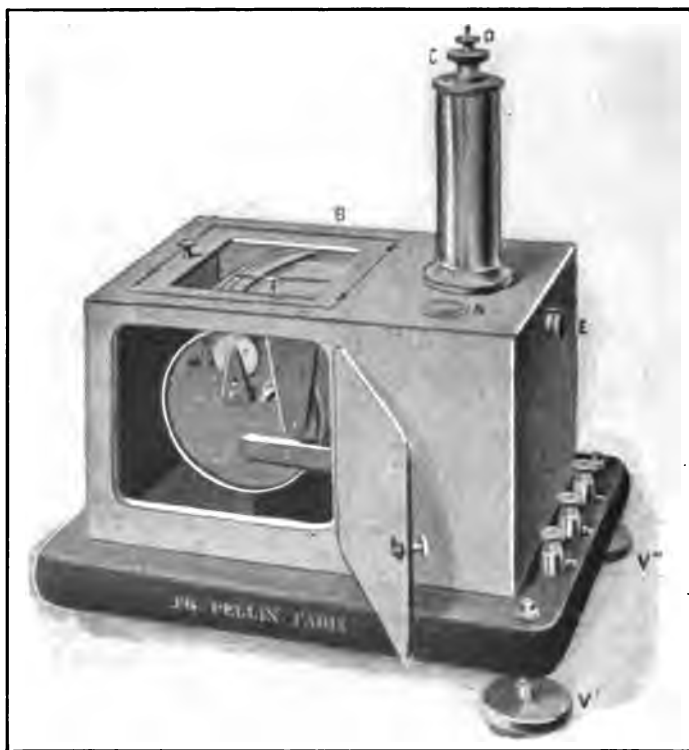


FIG 53.—PELLIN REGISTERING GALVANOMETER FOR LE CHATELIER THERMO-ELECTRIC PYROMETER.

gether eliminated, it is well to place a deadening pad of rubber between the coping and the pier. In order that the instrument give good readings, it must be perfectly level. It is well to check the level with a new pier, especially if there is any chance of settlement.

The coping of the pier can be made of a cast-iron plate about  $1\frac{1}{2}$  in. thick, with side lugs to be fastened to the cover-box of the instrument. The plate is purposely made thick to avoid placing any anchor-bolts. The cover-box is made with a glass top, and should be dustproof.

The needle of a galvanometer in good order swings freely, and any retardation in its free motion shows that some obstruction is in contact with the moving coil. The instrument cannot then be relied upon, and should be overhauled. If the galvanometer is kept in a dust-tight box the trouble is not likely to arise, as such

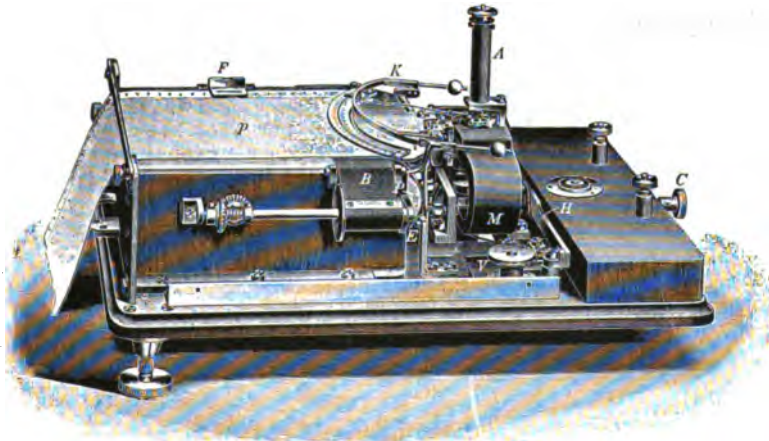


FIG. 54.—SIEMENS-HALSKE RECORDING GALVANOMETER FOR LE CHATELIER THERMO-ELECTRIC PYROMETER.

occurrence is due to careless construction; for this reason the instrument should be always thoroughly tested before use. Before moving instruments that are used at intervals for checking other instruments or for testing furnaces, great care should always be taken to fasten the needle very carefully, and it is also well to have for them a portable box especially built and well lined.

For blast-furnace work the insulation of the couples is effectively done by the use of hard glass tubing. The couples being permanently installed there is very little danger of breakage, since all that is required is the insulation of the two wires. For

the couple located in the down-comer, where it may be affected by slips, the best protection to the couple is given by placing the wires in the usual double-bore clay tubes and then wrapping them with asbestos cord. As has been said before, by using a couple made of silver or copper and constantan it is possible to use the Le Chatelier pyrometer for temperatures as low as  $100^{\circ}\text{C}$ ., and even lower.

For blast-furnace work, where the temperatures of the gas currents in the bustle and down-comer are always below  $1000^{\circ}\text{C}$ ., there is no possibility whatever of alteration of the couples. The writer knows of couples placed in the bustle-pipe of a furnace three years ago that are as good as when put in place. A com-

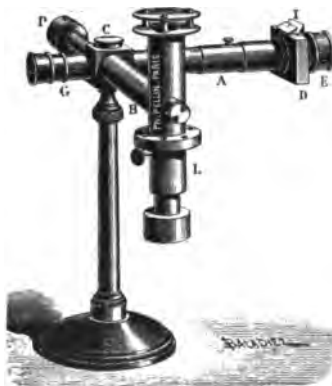


FIG. 55.—OPTICAL PYROMETER OF LE CHATELIER.

plete installation, with two recording galvanometers—one for the bustle-pipe, the other for the down-comer—with couples at six stoves with a direct-reading galvanometer, can be installed at considerably less expense than any other type of recording instrument; the indications, besides, will be found more accurate.

As we have seen, the Le Chatelier pyrometer, in spite of its many advantages, has its limitations. It can be used for intermittent temperature determinations up to the melting point of platinum, say,  $1780^{\circ}\text{C}$ . Above this temperature it is necessary to use pyrometers based on different principles. The field is left at this



range to the instrument making use of some optical properties or employing heat radiation. Several very good optical instruments have been brought out.

*Le Chatelier Optical Pyrometer.*—The Le Chatelier optical pyrometer and its modification, the Féry optical pyrometer, measure the intensity of the red radiations emitted by heated bodies. The field of vision in a telescope is divided in two halves, as in photometers; one half is lighted by a standard lamp, the other by the heated object under observation. The instrument having been calibrated by comparison with heated objects at known temperatures, it is possible to know the temperatures of an object having a given emissive intensity. The instrument gives remarkably accurate and concordant results, even in the hands of the inexperienced.

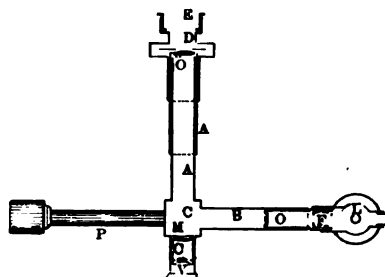


FIG. 55a.

By the nature of the instrument the observer is required to keep the eye at the objective, which causes fatigue if the observations are carried on for any length of time. With the Le Chatelier it is necessary to focus, while with the Féry the size of the object and its distance have no effect on the illumination.

The oil lamp is not convenient for use in places where draughts exist; it is better, then, to replace the oil lamp by a low-voltage incandescent lamp, the current being produced by a battery.

*Holborn and Kurlbaum, and Morse Pyrometers.*—These two instruments, built on precisely the same principle, have an incandescent lamp, the brightness of the filament of which is directly compared with that of the heated object. The current flowing through the filament is varied by a rheostat until the filament

disappears from view; the corresponding voltage is read on a voltmeter. By calibration against known temperatures the temperatures corresponding to the voltages have been established.

The shape of the filament—a horseshoe in the Holborn and Kurlbaum, a spiral in the Morse—constitutes practically the difference between the two instruments. The lower limit of the instrument is  $600^{\circ}\text{C}$ .

*Wanner Pyrometer.*—The light from a low constant voltage electric incandescent lamp and that from the heated object under observation are polarized. The instrument is a modification of König's spectrophotometer. The observer matches the illumi-

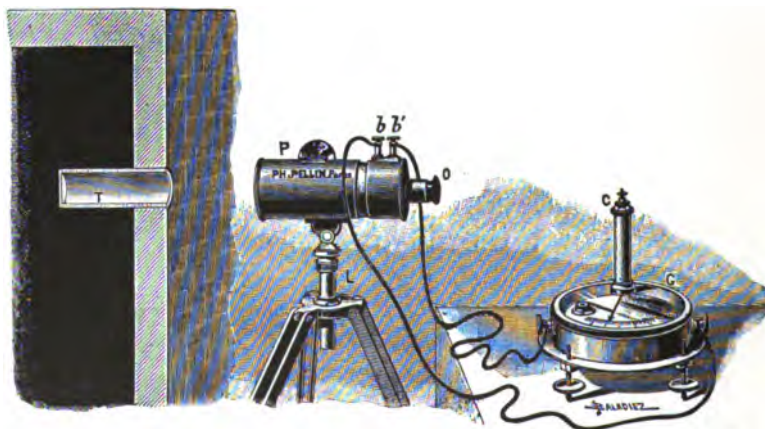


FIG. 56.—FÉRY HEAT-RADIATION PYROMETER.

nation of the standard half of the field by turning an analyzer. The angle through which the analyzer is rotated is a measure of the temperature. The instrument gives very concordant and accurate results. It cannot be used below  $900^{\circ}\text{C}$ .

*Remarks.*—These optical instruments in the hands of trained men can give accurate results; however, they all present the same difficulty—that of matching two illuminated surfaces, thereby requiring the constant attention of the operator. Care has to be taken in regard to the age of the lamp and the constancy of the

current. The indications of the instruments are not reliable if the heated object is strongly lighted by sunlight.

*Heat-Radiation Pyrometer.*—The heat radiated from a heated object varies according to Stephan's law (mathematically demonstrated correct on thermodynamic considerations), as the fourth power of the absolute temperature. In the Féry radiation pyrometer the heat radiated is measured by means of a very sensitive thermo-couple, formed of constantan and copper (constantan being an alloy of 75% copper and 25% nickel). The thermo-junction is heated and an E. M. F. is generated, the measure of which is given by a d'Arsonval galvanometer. The instrument is calibrated by comparison with the Le Chatelier thermo-electric couple up to the melting point of platinum; above that by extrapolation.

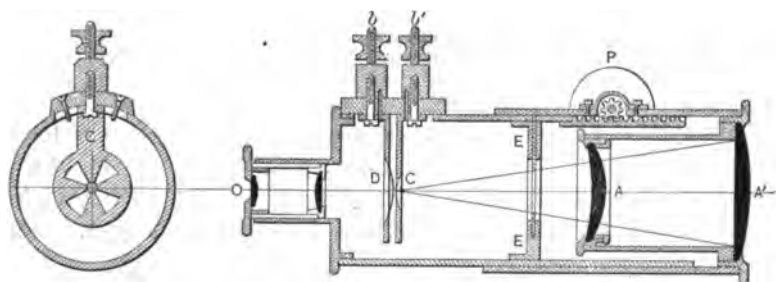


FIG. 57.—FÉRY HEAT-RADIATION PYROMETER, LENS TYPE.

In Fig. 57 is given a section of the instrument. The thermo-electric couple is formed by two extremely thin wires supported by *D* and *C*, electrically connected to the binding-posts *b*, *b'*. In front of the couple is placed a cross-shaped metallic screen, *C*, which leaves only the thermo-junction exposed. Once the image of the body under observation covers the thermo-junction, the instrument becomes independent of the dimensions of the object.

The minimum distance is 1 m., for which distance the minimum diameter of the object must be 3 cm. With a larger diameter the distance of observation may be largely increased; for example, with a diameter of 60 cm. the instrument may be placed at 20 m.

The instrument has to be focused for each distance; however,

the indications are rendered independent of the distance by means of the diaphragm *E*, the cone of heat rays falling on the thermo-junction having thereby a constant angle, whatever the distance.

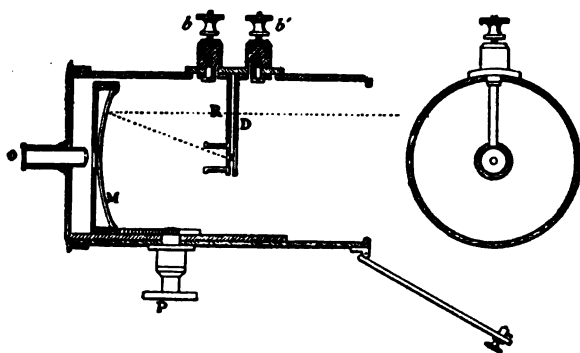


FIG. 58.—FÉRY HEAT-RADIATION PYROMETER, MIRROR TYPE.

This type of apparatus is well suited to the observation of temperatures above  $900^{\circ}\text{C}$ . Below this, and in fact up to  $1100^{\circ}\text{C}$ ., the absorption of the heat radiations by the lenses is unduly high. The instrument illustrated in Fig. 58, of the telescopic type, has a

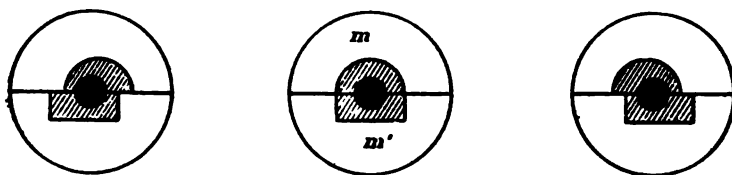


FIG. 59.—FOCUSING DEVICE OF THE FÉRY HEAT-RADIATION PYROMETER, MIRROR TYPE.

sensitiveness ten times that of the other for the lower range of temperature. It will give correct readings down to  $300^{\circ}$ . The instrument has the same construction as to the means of eliminating the factors of distance and dimension of the objects under observation.

The correct focusing is assisted by two small mirrors, *m*, *m'*,

through the use of which the image of the object appears distorted when the focus is taken too short or too long (as shown in Fig. 65). As the thermo-couple is never exposed to temperatures of above  $80^{\circ}$  C. as a maximum, it preserves absolutely the constancy of its E. M. F. The instrument once set up, sighted and focused, no



FIG. 60.—CAMBRIDGE SCIENTIFIC INSTRUMENT COMPANY DIRECT-READING GALVANOMETER FOR THE FÉRY HEAT-RADIATION PYROMETER.

further adjustment is required. The temperature of the body is automatically shown on the dial of a dead-beat galvanometer, giving, therefore, practically instantaneous readings.

The instrument being absolutely free of the personal equation, any workman with ordinary intelligence, without previous training, can make accurate observations. The indications of the instruments are not affected by the extraneous lighting of the observed body, which may be an ingot under treatment through rolls or under presses. The instrument is also made self-registering.

## CHAPTER XII.

### GAS ANALYSIS.

The methods here given apply only to technical analysis in which results correct to within 0.5% are amply sufficient. The gases to be analyzed may contain the following: Oxygen, carbon dioxide, carbon monoxide, hydrogen, methane, ethane, ethylene, nitrogen, water vapor, etc.

In producer-gases, with which we have mainly to deal, the heavy hydrocarbons seldom occur over 0.5%, and it is usually sufficient to reckon them as heavy hydrocarbons without further differentiation. It is of prime importance that the analyses be made in the shortest time possible.

In large works it is often impossible to have a special laboratory located conveniently to the various furnaces; in such cases it is necessary to utilize the first handy location. It follows that, for technical analyses, preference should be given to methods requiring simple apparatus and a minimum time. All methods in which mercury is used should be discarded. Determinations made with explosion burettes and eudiometers filled with water cannot be regarded as accurate, as the pressure exerted during the explosion is sufficient to dissolve a large amount of the carbon dioxide formed. It is also often necessary, for weak mixtures, to add oxyhydrogen gas, which requires a generating apparatus. The method of burning the gases by means of a spiral of platinum wire necessitates the use of an electric current.

The method here outlined has been found to give sufficiently accurate and concordant results with a minimum expenditure of time and apparatus. The water vapor is absorbed by a Liebig bulb filled with concentrated sulphuric acid. This is done very conveniently while the sample is being taken. The carbon dioxide is absorbed by a 33.3% solution of potassium hydrate, the heavy

hydrocarbons by strong bromine water, and the oxygen by an alkaline solution of pyrogallie acid ; carbon monoxide is absorbed by an acid cuprous chloride solution. The hydrogen and methane remaining are burned by means of a Dreschmidt capillary platinum tube, the carbon dioxide formed being absorbed in a potash solution. A complete gas analysis can thus be performed in an hour, or even less, the time varying according to the skill of the operator.

*Sampling.*—This can be done by introducing a piece of gas-pipe into the flue, the pipe being of such length that its opening will reach about the middle of the flue. The pipe should be large enough to allow the placing of a loose wad of asbestos fiber to collect any dust, soot and tar that may be present in the gas. If the flue is built of bricks, the work is quite simple; if the flue is of sheet iron, in order to have the pipe reach inside it is convenient to use the shape of pipe illustrated in Fig. 61. The required length of pipe to be introduced in the flue is reduced in diameter so that it will easily pass through the hole drilled for the main portion of the pipe; thus the hole is tapped and the conical shoulder threaded. It is convenient to reduce the diameter of the pipe at the other end to about one-quarter inch in order to screw on a quarter-inch gas-cock.

*Sample Tubes.*—The tubes have a capacity of about 300 cc., with capillary ends provided with three-way stop-cocks, as shown in Fig. 61. These cocks are very convenient, as they allow the removal of air, always present in the open end. The tubes, generally a set of twelve, are handily carried in a box made especially for them.

It is better not to fill the tubes with water before the taking of the samples, as in all instances it is well to pass a rather large amount of gas through the tube, the last trace of enclosed air being thus removed. In very cold weather, if the flue is exposed to the outside temperature, it is almost impossible, if the tubes have been filled with water, to prevent the freezing of the water in the capillaries. In all technical analyses the determination of the water vapor should always be made. In the making of producer-gas, it is usual to consume fully 10%, and sometimes 15%, of the total fuel burned on the steam-boiler grate; the water-vapor con-

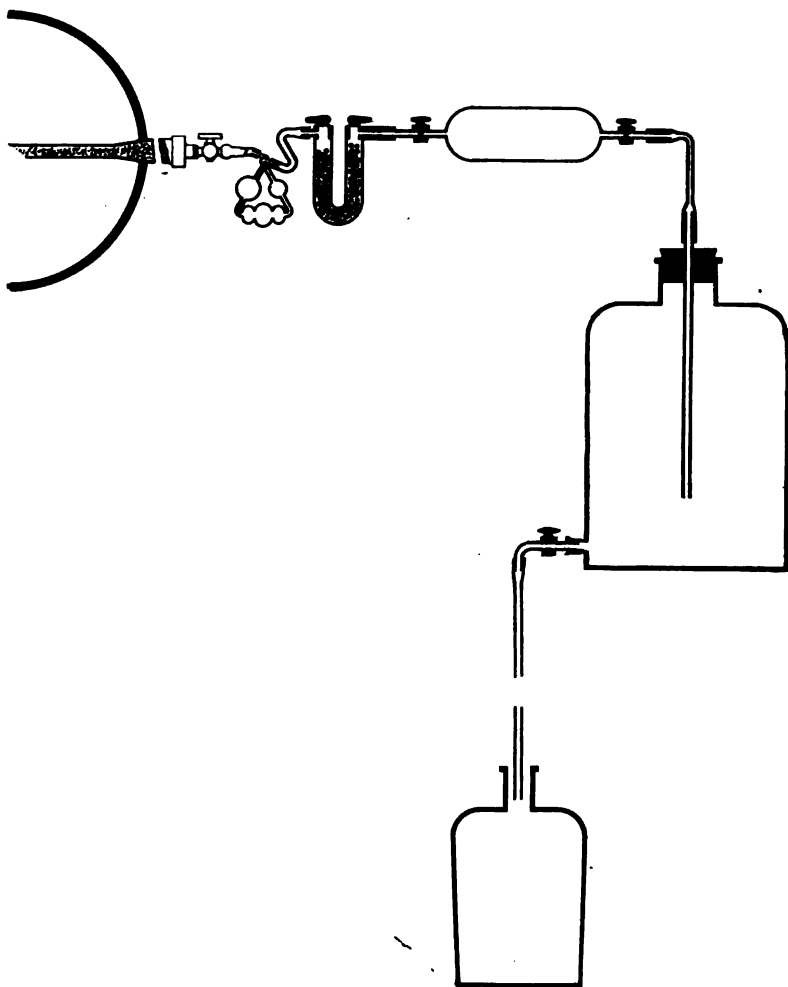


FIG. 61.—APPARATUS FOR THE DETERMINATION OF WATER VAPOR IN GASES. The Sample Tube is shown inserted between the Mariotte Flask and the Safety Sulphuric-acid U-Tube.

tents will give in all cases important indications; the determination is, as we have seen, absolutely necessary in making furnace tests.

*Water-Vapor Determination.*—This can be done either by the



determination of the dew point, as shown by Mahler<sup>1</sup>, or preferably, in industrial practice, by actual weighing. A fixed volume of gas, at least three liters, is passed through the Liebig tube on its way to the sample tube (Fig. 61). The gas is drawn under a constant head of water by means of a Mariotte flask, of 5 liters or more capacity. The weight of the Liebig bulb being determined before and after the operation, the difference in weight will give the weight of the water vapor contained in the volume of gas taken; knowing the molecular weight of the water vapor, 18 grams for the molecular volume 22.32 liters, it is an easy problem to find the corresponding volumetric percentage of the condensed water weighed.

The Liebig bulb should be connected to the gas-cock with as short a piece of tubing as possible, the length of the iron sample-tube being such that the temperature of the cock will never be so high as to cause the rubber to soften and distillate; on the other hand, it should not be so long that the temperature of the issuing gases will fall below 100° C. This is very important in order to avoid the premature condensation of the water vapor. The red or white tubing is better suited for this connection than the black, as it will stand a higher temperature.

The quantity of gas passed through the Liebig bulb is ascertained by catching the water escaping from the Mariotte flask, in a vessel of known capacity. If the volume of the recipient is 3 liters or over, it will be sufficiently accurate to measure the water used, without having recourse each time to weighing.

The Liebig bulb is followed by a U-tube filled with glass beads, moistened with concentrated sulphuric acid, in order to prevent the contamination of the Liebig bulb by the water vapor from the Mariotte flask. One Liebig bulb is always sufficient for the total absorption of the water vapor; trials have been made with two bulbs, and the second one never increased in weight. It is convenient to make a frame to carry the train of apparatus.

With strong stack draught it may be found that the gas will not flow; this is easily remedied by increasing the length of the discharge tubing from the Mariotte flask, thus increasing the head. As in all other chemical work, for accurate results it is of prime

<sup>1</sup> P. Mahler. "Etude sur les Combustibles, Solides, Liquides, Gaseux," p 51.

importance to perform all operations, as far as practicable, under the same conditions.

The room selected for the analytical work should be kept, as far as possible, at a uniform temperature. A large supply of water necessary for the various determinations should be kept in a suitable reservoir, so that the water used in the analytical process shall be at the prevailing temperature of the room.

For practical purposes, it is better to use pure water rather than a saturated solution of sodium or magnesium chloride, as the salt solutions, by capillary action, cause a deposit of the salt in all the joints and cocks of the apparatus used.

It is well, to insure accuracy, to saturate the water used with the gas in use. The composition of the producer-gas in a plant using the same grade of coal and in good running condition is very nearly constant; it is then sufficient to pass a stream of the gas through the bottle; this will insure a constancy of condition better than the using of salt solutions. Since the method selected is rapid, requiring in the hands of a trained man less than an hour's time for a complete analysis, it follows that it is an unnecessary refinement to make corrections for temperatures, vapor tensions and barometric pressure. If this is thought desirable, however, it is a simple matter. The errors resulting from this neglect, when the work is otherwise properly conducted, are usually of a smaller order than the other errors introduced by the use of water, unsaturated reagents, errors of reading, etc.

Several very good forms of apparatus can be used for technical gas analyses, all giving satisfactory results. In order of accuracy, we may mention the Hempel, the Elliott and the Orsat. This order is changed if the rapidity of the determination is considered;<sup>1</sup> it then becomes the Elliott, the Hempel and the Orsat. For technical work when the analyses have to be made in rooms not especially adapted to the purpose, the writer gives preference to the Elliott apparatus, which has only one absorption tube. The apparatus is placed in a fixed position, and there is very little chance of breakage. With the Hempel apparatus a number of absorption

<sup>1</sup> A new type of Orsat apparatus has lately been put on the market. The gas under analysis is made to bubble through the reagent's burettes: the time of absorption is thus much reduced.

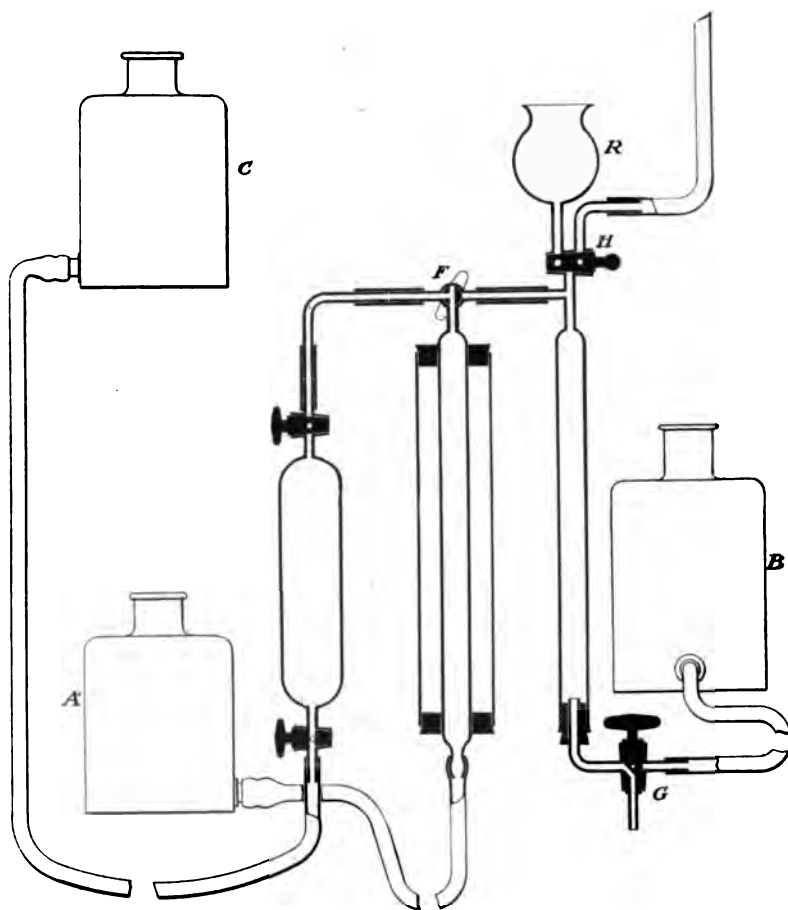


FIG. 62.—ELLIOTT APPARATUS FOR GAS ANALYSIS.

pipettes are required, and unless a troublesome record of the quantity of gases absorbed by each pipette is made errors may be introduced by the use of too old reagents. The manipulations are also much more complicated than with the Elliott modification of the Bunte burette, as fresh reagents are introduced every time; this, naturally, means an extra waste of materials.

We will confine ourselves to the description of the method we

have followed in the Elliott gas apparatus. For the description of the Hempel apparatus, we will refer to the excellent work of Dr. Hempel on the subject. It is very important that the determinations be conducted under similar conditions.

The filled sample tubes are left to stand in the room long enough to reach the surrounding temperature. The burette readings are to be made always after the same lapse of time. This is to give the water the same time to run down the walls of the tube; for this purpose a small sand-glass is very convenient. The same volume of gas, to within a few cubic centimeters, should be taken for analysis each time. It is useless to try to measure an exact number of cubic centimeters—say one hundred—since, with methane present, calculations are always necessary. The calculations are, furthermore, very simple, especially with the use of a slide-rule<sup>1</sup>. The same quantity of wash-water should be used in each case, care being taken to avoid handling the tubes, as the heat conducted suffices to vitiate the results. If all these precautions are taken, even with unsaturated reagents, an accuracy of 0.5% is attainable with the Elliott apparatus.

*Potash Solution.*—A solution of 33% strength is made by dissolving one part of commercial potash sticks in two parts of water. It is well to make enough at one time to last for a large number of analyses, as it cannot be used immediately after preparation on account of the exothermic reaction, the solution becoming very hot.

*Bromine Water.*—A saturated solution is obtained by placing 100 cc. of bromine in 900 cc. of water; it is not necessary to introduce any of the bromine in the absorption tube, the saturated water solution being sufficient.

*Alkaline Solution of Pyrogallol.*—Five grams of pyrogallol are dissolved in 15 cc. of water; in another beaker 80 grams of commercial potash are dissolved in 200 cc. of water; the two solutions are then mixed. The solution must be kept in a well-corked bottle, to prevent the access of air.

*Cuprous Chloride Solution.*—The choice lies between the ammoniacal solution of cuprous chloride, or an acid solution. The acid solution has a more energetic absorbing power and is more easily prepared.

<sup>1</sup> The 7-in. Sexton omnimeter, a circular slide-rule, is particularly serviceable

Many tests have satisfied the writer that one absorption with about 25 cc. of the fresh solution will completely remove the carbon monoxide. The solution is prepared as follows: 1000 grams of cuprous chloride are placed in a 2500 cc. bottle; 1000 cc. of water are added, then 250 cc. of concentrated hydrochloric acid; as many lengths of copper wire are introduced as is convenient, and the bottle is then filled with water to the neck and a good rubber stopper inserted. The bottle is thoroughly shaken. The solution will be turbid and brown-colored at first, but after 24 hours will become thoroughly limpid; it is better to have the

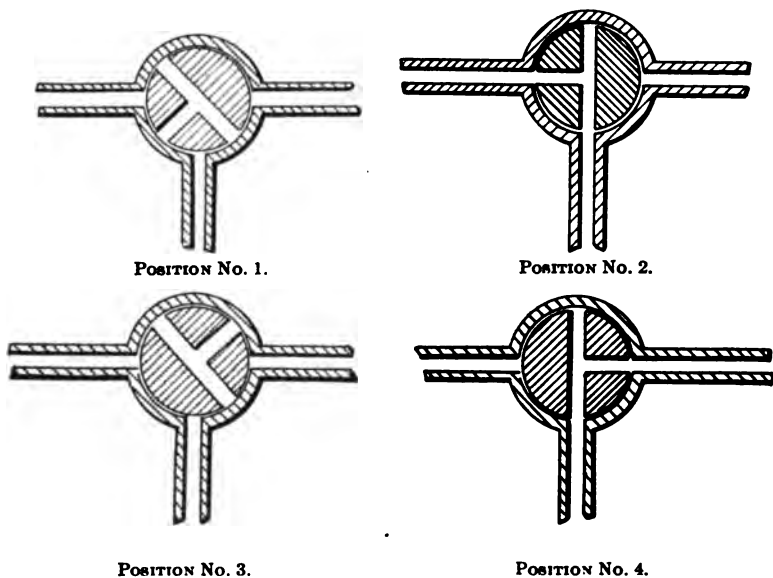


FIG. 63.—SHOWING THE VARIOUS POSITIONS OF THREE-WAY COCK, F.

solution in a dark-colored bottle, as the light affects it. The measuring-tube is protected from sudden changes of temperature by means of an air-jacket; water may be used, but is not necessary.

*Manipulation.*—The sample-tube, having reached an equilibrium of temperature, is connected with the water-bottle by means of rubber tubing on which a pinch-cock is inserted. The air in the tube and in the capillaries is forced out by water before the three-

way cock is opened. The upper capillary of the sample-tube is now connected with the measuring burette by means of a capillary ell, and the air in the connections is removed by forcing water through the three-way cock of the burette, by bringing the water-bottle *A* to the upper level. The bottle *C* is placed on the table, and the cocks of the sample-tube as well as cock *F* of the burette are opened to position No. 2; the gas will now flow in the burette. When the proper amount has collected, *F* is changed to position No. 3. The upper three-way cock of the sample-tube is also closed, and the capillary connection between the burette and the sample-tube removed. The volume of gas in the burette is read by raising bottle *A* until the levels of the water in the bottle and in the burette are on the same horizontal plane. The reading

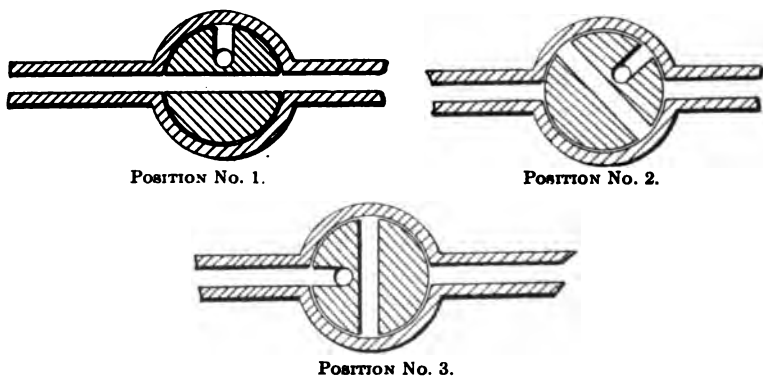
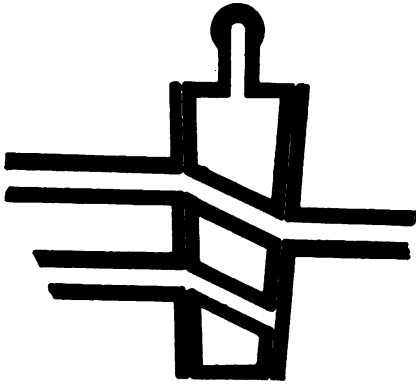
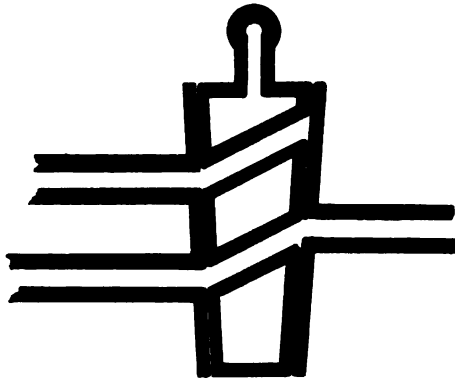


FIG. 64.—SHOWING VARIOUS POSITIONS OF THREE-WAY COCK, G.

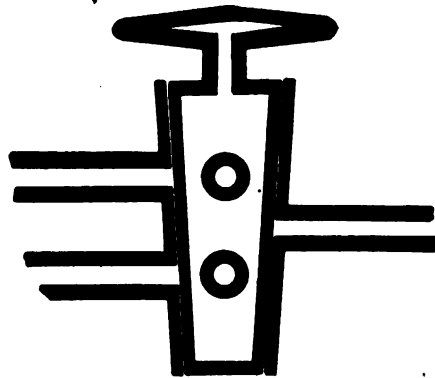
is noted, the bottle *A* raised to its upper position, the bottle *B* lowered to the table, and the cock *F* is opened to position No. 4, and cock *G* to position No. 1. The gas is now confined in the absorption tube. Cock *G* is brought to position No. 2, and *F* to position No. 3. The gas is then under a slight depression. The reagent cup *R* is filled half-way with the potash solution, and cock *H* is turned to position No. 2, so that the solution will flow uniformly in small ripples down the walls; when the solution ceases to flow, or merely flows more slowly, cock *G* is turned to position No. 3, very slowly; special care is to be taken here to



No. 3.



No. 2.



No 1.

FIG. 65.—SHOWING THE VARIOUS POSITIONS OF THREE-WAY COCK, H.

avoid an inrush of air. Cock *H* is turned to position No. 1 as soon as the potash solution nears the capillary. *F* is opened for a few seconds to wash the connection, after it has been brought to position No. 3. *H* is brought to position No. 3, and a small amount of wash-water is allowed to flow; *H* is then turned to position No. 1.

The gas, which is now free of carbon dioxide, is to be brought back to the measuring burette; to effect this operation the bottle *B* is brought to a higher level, *G* is turned to position No. 1, and *F* to position No. 4; the bottle *A* is lowered to the table; the gas will now flow into the burette; the water is allowed to flow in the capillary down to the zero mark, *F* is turned to position No. 3, and, as before, the volume of the gas is measured with the usual precautions.

If the gas contains ethylene,  $C_2H_4$ , the next absorption will be by means of bromine water; the potash solution left in the absorption tube must first be thoroughly removed. If no ethylene is present, the next absorption is by means of an alkaline solution of pyrogallol acid; the potash need not be washed out in this case.

To wash the absorption tube, *G* is turned to position No. 3, and *H* to No. 2; the tube is thereby emptied, and wash-water is introduced into the cup, a little at a time; the flow must be regulated so that the water will run entirely along the walls; finally *H* is brought to No. 3, and some more wash-water allowed to flow. *H* is then turned to position No. 2, *G* to position No. 1, and the absorption tube is filled until the water overflows into the cup *R*. Bottle *B* is then lowered to the table, *A* is brought to the upper level and *F* is turned to position No. 4, the gas being transferred to the absorption tube. The cycle of operations is now the same. The bromine water is introduced into the tube; to remove the vapors of bromine which have a high tension, some potash solution is introduced after absorption. The gas is then removed to the burette and the contraction measured as before.

*Oxygen*.—The next gas to be determined is oxygen. The absorption is effected by means of the alkaline pyrogallol solution. When no ethylene is present, this absorption is effected immediately after that of the carbon dioxide, the potash solution being left in the absorption tube. Care should always be taken



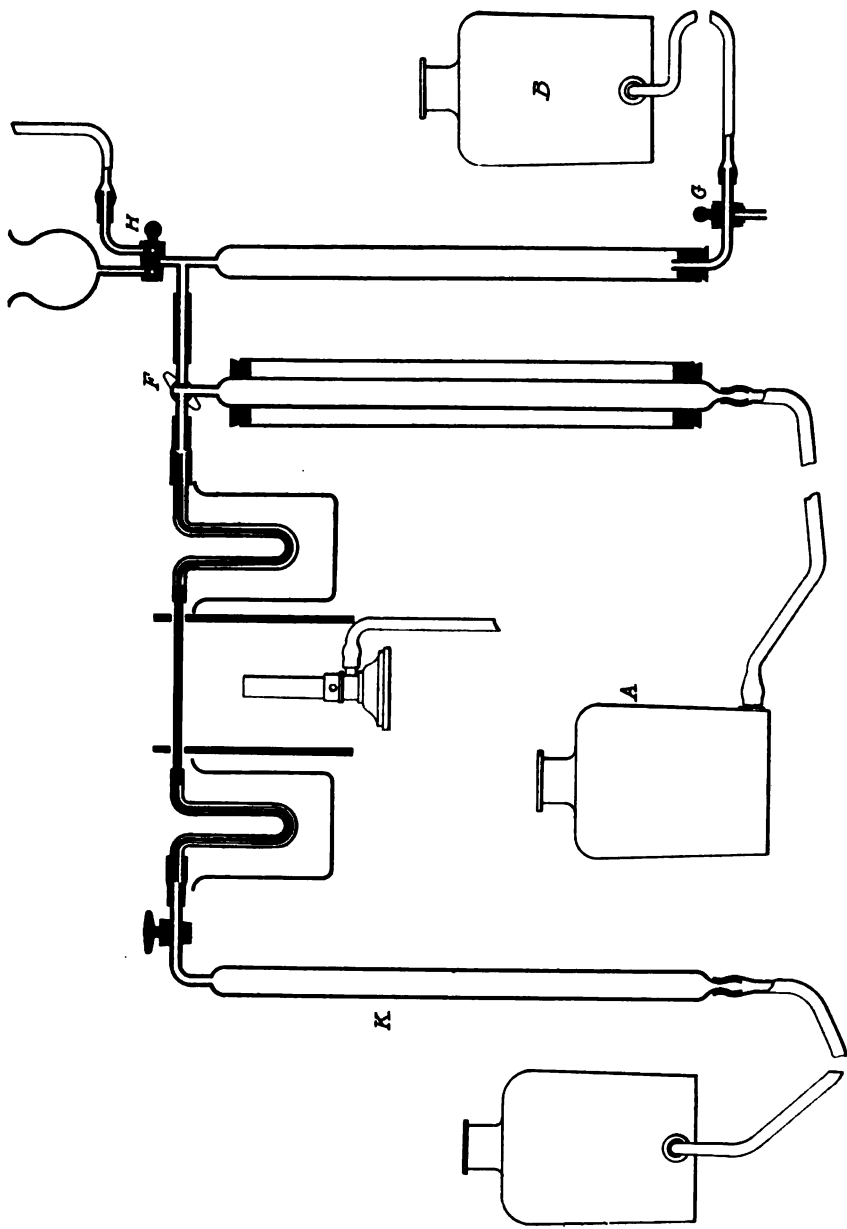


Fig. 66. - ELLIOTT APPARATUS FITTED WITH DREHSCMIDT PLATINUM TUBE FOR THE DETERMINATION OF HYDROGEN AND METHANE.

to remove the reagent solutions from the upper part of the absorption tube and in the capillary connection, in order not to contaminate the water contained in the measuring burette. The manipulation given under the determination of carbon dioxide should be adhered to. The pyrogallol solution is to be thoroughly removed before the next absorption, that of carbon monoxide.

*Carbon Monoxide.*—The acid cuprous chloride solution is introduced into the tube, about 25 cc. being used. The solution is allowed to flow freely along the walls, this being easily accomplished by having the tubes of the apparatus in a vertical position. The tubes, however, should be thoroughly cleaned before erecting them, to remove any greasy film that would prevent the solutions from wetting the walls.

Though the vapor tension of the cuprous chloride is small, it is better to introduce some potash solution before passing the gas into the burette in order to absorb the vapors of hydrochloric acid. The volume of gas remaining is measured, and the contraction is equal to the amount of carbon monoxide present in the gas. The remainder of the gas consists now of hydrogen, methane and nitrogen.

*Hydrogen.*—The gas can be burned by passing it over palladium asbestos; below 100° the methane is not affected. In any event, combustion has to be resorted to for methane. It appears, therefore, quicker to subject both gases at the same time to combustion.

We have seen that, with water as the confining liquid, explosion is not to be recommended. The combustion is effected by using the Drehschmidt tube or the Coquillon platinum spiral, heated by an electric current. For practical purposes preference is to be given to the Drehschmidt tube, which requires no electric current, but simply a gas-jet or an alcohol lamp.

*The Drehschmidt Tube* consists of a capillary platinum tube 100 mm. long with a diameter of about 0.7 mm. internal, and 2.5 mm. external. The tube is soldered to the copper tubes at each extremity, as shown in Fig. 72. The ends of the platinum tube should extend for about 10 mm. inside the copper tubes, so that the soldering may be thoroughly cooled. The copper tubes are about 2.5 mm. inside diameter, 3.5 mm. outside, and are U-shaped.

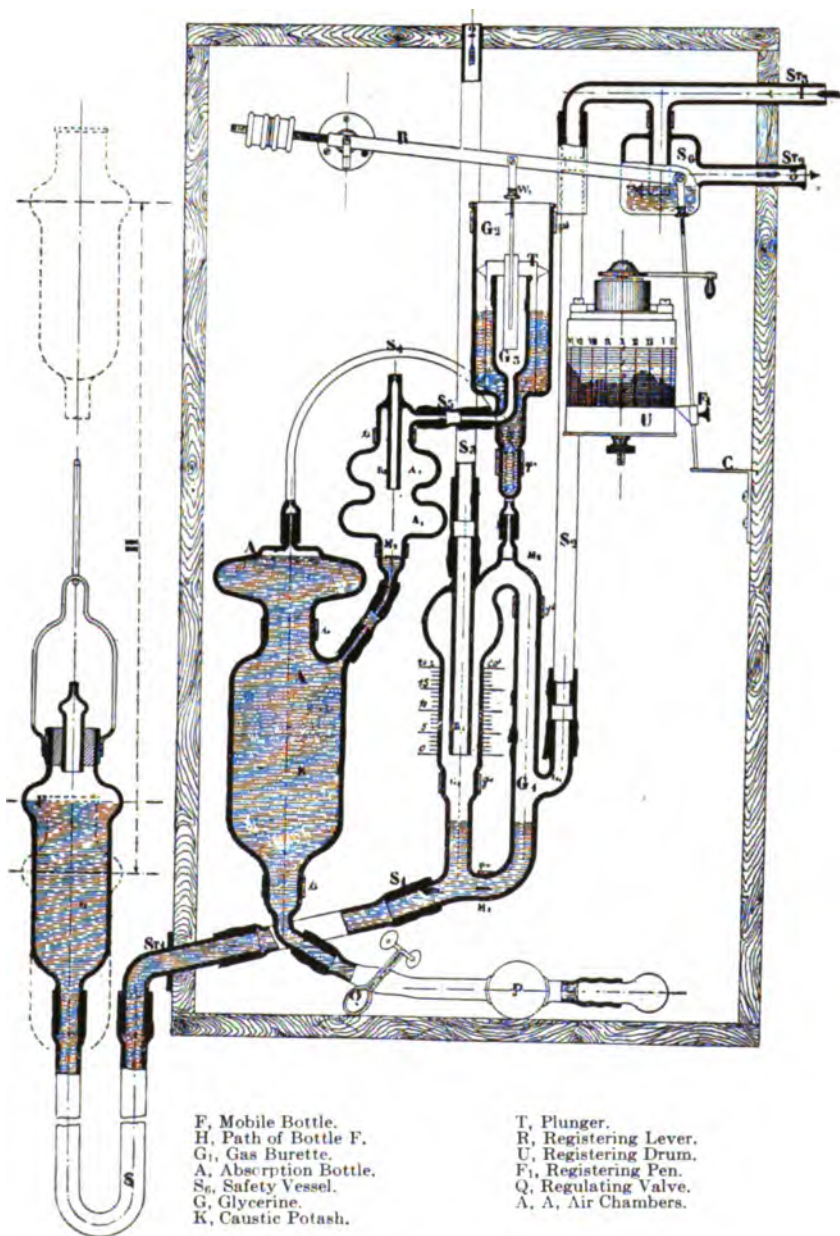


FIG. 67.—SECTION OF THE "ADOS" AUTOMATIC GAS ANALYZER.

Four or five platinum wires are inserted throughout the length of both the platinum and copper tubes; the wires may be 0.008 mm. in diameter.

The two copper tubes are to be thoroughly cooled; an easy way is to insert the U portions of the tubes in deep beakers filled with water, the beakers being protected from the radiation of the flame by asbestos cardboard. Cooling by means of a stream of water is to be avoided, as it requires rather complicated apparatus.

The combustion is effected in the capillary tube through the catalytic action of the platinum at a good cherry heat. The wires assist in giving additional points of contact, and they also decrease the free volume inside of the tube; in case of rich mixtures there is a possibility of an explosion. There is little likelihood, however, of its being carried back into the burette, on account of the low temperature existing in the copper tubes, which would bring the gas below the explosion temperature.

The apparatus required for the use of the Drehschmidt tube is shown in Fig. 66. The tube is connected with the two burettes by means of rubber tubing. The gas is transferred to burette *K*, and enough air, with about 10% excess, is then introduced to insure the complete combustion of the gases. The total volume of the gases is measured. The tube is thoroughly shaken to promote a good mixture. The burette is again connected with the copper tube; meanwhile the heating apparatus is placed under the platinum tube. When the tube has been brought to a cherry heat the gases are passed slowly through the tube from one burette to the other. Care is to be taken to avoid introducing any water into the copper tubes. The gases are passed four or five times, the last pass bringing them in the measuring burette. *F* is turned to position 3, the Drehschmidt tube is removed and the contraction measured. The gas is then removed to the absorption burette for the absorption of the carbon dioxide produced. By a simple calculation the percentage of hydrogen and methane is obtained. The nitrogen is found by difference. The temperature in the Drehschmidt tube is too low to result in the partial combustion of the nitrogen.

*Calculations.*—As all the operations can be performed in considerably less than an hour, no corrections need be made for temperature and pressure. The percentages of carbon dioxide, ethylene, oxygen and carbon monoxide are found by dividing the corresponding measured contractions by the original number of cubic centimeters.

Hydrogen, Methane and Nitrogen.

Let  $H_2 = x$        $CH_4 = y$        $N_2 = z$

if  $V$  = original volume,

$C$  = Contraction after explosion.

$D$  = Volume of carbon dioxide produced.

We have, then (since one volume of hydrogen combines with one-half volume of oxygen to form water), for one volume of hydrogen a contraction equal to one and a half times that volume.

Also, since one volume of methane combines with two volumes of oxygen to form one volume of carbon dioxide, there results a contraction equal to twice its volume:

$$x = \frac{2C - 4D}{3} \text{ in } \% \quad x = \frac{(2C - 4D) 100}{3A}$$

$$y = D \quad y = \frac{100D}{A}$$

*Water Vapor.*—Let the volume of gas passed through the Liebig bulb be 3450 cc., the increase in weight being 67 mg.

The molecular weight of water vapor is 18 grams for the molecular volume 22.32 liters; or, per liter,  $\frac{18}{22.32}$  grams.

For 3450 cc. we have  $\frac{18 \times 3450}{22.32} = 2782$  mg.

The true percentage of water vapor for 67 mg. is then

$$\frac{67 \times 100}{2782} = 2.40\%.$$



*Automatic Self-Registering Gas-Analyzing Machine.*—It is very important to be able to keep a record and at the same time a control of the composition of gases, such as producer-gas or products of combustion. Up to date it has not been possible to make practically more than one determination, that of carbon dioxide,  $\text{CO}_2$ . This is, however, sufficient in most instances, as generally the same coal or fuel will be used at a given plant.

In producer-gas, there is a certain relation between the total number of molecules of carbon contained in combination, and the molecules held by the different gases,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{CH}_4$ . The knowledge of the volumetric contents in  $\text{CO}_2$  will allow a fair estimate of the remaining components being made.

In Fig. 67 is illustrated a section through the analyzer of the Ados<sup>1</sup> gas-machine. The gas to be analyzed is drawn from the flue by means of a very ingenious double-acting air-pump, operated by the draught of the furnace stack. A fixed volume of gas, 100 cc., is passed through the absorber, *A*, containing a strong solution of  $\text{KOH}$ ; thence the gas, minus the  $\text{CO}_2$ , is sent to the measuring vessel, *G*. A line proportional in length to the remaining volume of gas is drawn automatically on the paper wrapped around the drum, *U*. A sample may be taken every four minutes, or at greater time intervals, the apparatus being regulable at will. Glycerine is used to fill the apparatus. A gas-filter is provided, as it is necessary in the case of bituminous producer-gas.

The apparatus has been introduced in a number of large European works, especially in connection with boilers. Fig. 68 shows the 24-hour record of a boiler. The firemen are paid premiums according to the carbon contents of the waste products.

The apparatus has also been installed, lately, on the producer batteries at the Hazard works of the New Jersey Zinc Company.

<sup>1</sup> Made by E. Dégremont, Le Cateau, France.

## CHAPTER XIII.

### CALORIMETRY.

Data concerning fuels cannot be complete, or even regarded as satisfactory, unless the heating value or calorific power be included. This expression of its latent energy is of primary importance in the valuation of most fuels, as it affords a basis of comparison both as to relative value and as to the possible heat utilization.

It would seem, at first, possible to calculate the calorific power of coal from its chemical analysis. And so we could were the compounds present accurately known, but though many attempts have been made, none have met with signal success. The most reliable formula for the heating effect of a coal, burned to liquid water, is that of Dulong, which gives the calorific power in calories per kilogram.

Calorific Power equals  $8080 C + 34460 (H - \frac{1}{8} O) + 2250 S$ .

Attempts to plot the calorific power and analysis graphically and thus arrive at a general rule, or graphic method, of arbitrarily determining the heating value of an unknown coal, have not been satisfactory.

Knowing the chemical analysis or composition of an oil or gas, we can calculate its calorific power quite accurately, but in many, perhaps most, cases the complexity of composition is such that a direct determination is preferable.

The calorific power, expressed in the centigrade-kilogram or Fahrenheit-pound units, is found by actually burning the fuel under known conditions and noting the heat evolved; usually by absorption by water. It is, therefore, not simply a theoretical property of the fuel, but represents actually the heat evolved when at particular fuel is burned.



The form of apparatus employed will vary somewhat with the state of the fuel, whether solid, liquid or gaseous; but omitting the Thompson calorimeter, which was liable to as much as 15% error, we have at present various modifications of three standard forms:

- (1) The *Bomb Calorimeter*, originally devised by Berthelot.
- (2) The *Parr Calorimeter*.
- (3) The *Junker Calorimeter*.

The first of these, under the Mahler, Atwater, etc., modifications, is the most accurate calorimeter known, and is suitable for the combustion of fuel either solid, liquid or gaseous. The Parr is suitable only for use with solid or liquid fuel, and the Junker for liquid or gaseous fuel only.

The following descriptions will render clear the mechanism and actual procedure to be followed in the use of these instruments.

#### THE BOMB CALORIMETER.

The general principle upon which this apparatus is based is the combustion, by means of oxygen, of the material in an enclosed space without addition or subtraction of material during the operation. The total heat evolved can thus be absorbed by surrounding the apparatus completely with water, the rise in temperature being noted. To insure an excess of oxygen gas, by which a complete combustion is secured, a pressure of about 20 atmospheres is used. The ignition is brought about by electrically heating to incandescence a small coil of wire in contact with the substance to be burned.

The vessel or bomb within which the combustion takes place is a strong, seamless, cylindrical steel shell provided with a close-fitting cap which screws over the open end. To prevent oxidation of the iron shell during the combustion and corrosion by the nitric and sulphuric acids formed, it is necessary to line the shell with platinum or enamel the interior (Mahler). More recently Atwater has used a gold-plated copper lining which has advantages over the older forms. A description of this latter form of apparatus, with a few explanatory remarks, will suffice for all the modifications

now in use. To enumerate the different parts of the apparatus we have:

(1) The calorimeter, including the bomb, a thin brass cylinder or pail to contain the water surrounding the bomb, a thermometer, and the stirring mechanism.

(2) The outer envelope, enclosing the calorimeter system; designed to render the loss or gain of heat as uniform and slow as possible.

(3) Supplementary apparatus for filling the bomb and compressing the fuel and also effecting its ignition, etc. This includes the pressure gauge and couplings, a clamp and spanner to hold and close the bomb, a briquetting device for compressing the fuel, and a motor for stirring the water.

The bomb shown in Fig. 69 is self-explanatory, the substance being held in the capsule *C*. Oxygen is admitted under pressure at *O*, and is retained by closing the valve *V*. The joint between body and cap is made tight by a lead gasket, which is pressed by the annular V-shaped edge of the body. The V-shape is a great improvement over the older flat surface. Ignition is effected by passing a current of about 5 amperes through the insulated post, *P*, to the coil of fine iron wire, *W*, just above the combustible matter. This wire is heated to ignition by the current, which finds its way to the body of the bomb and thence completes the circuit by a connection at *V*.

The lining which covers the interior surface of the shell and cap has been made of platinum, enamel and gold-plated copper. The two former labor under the disadvantage that platinum is very expensive and the enamel will crack and flake off, exposing the iron. The gold-plated copper is satisfactory and durable, but it or any other removable lining must be carefully fitted to prevent the compressed gas from finding its way between it and the shell; otherwise the lining will be completely destroyed upon the release of the interior pressure. The convenience of removal, however, outweighs this objection, which may be avoided with care.

When in use the bomb is immersed in water contained in a thin brass pail, of such dimensions that the bomb is completely covered

and sufficient room is left so that there is a certainty that no water shall splash over during the stirring. This pail must be kept

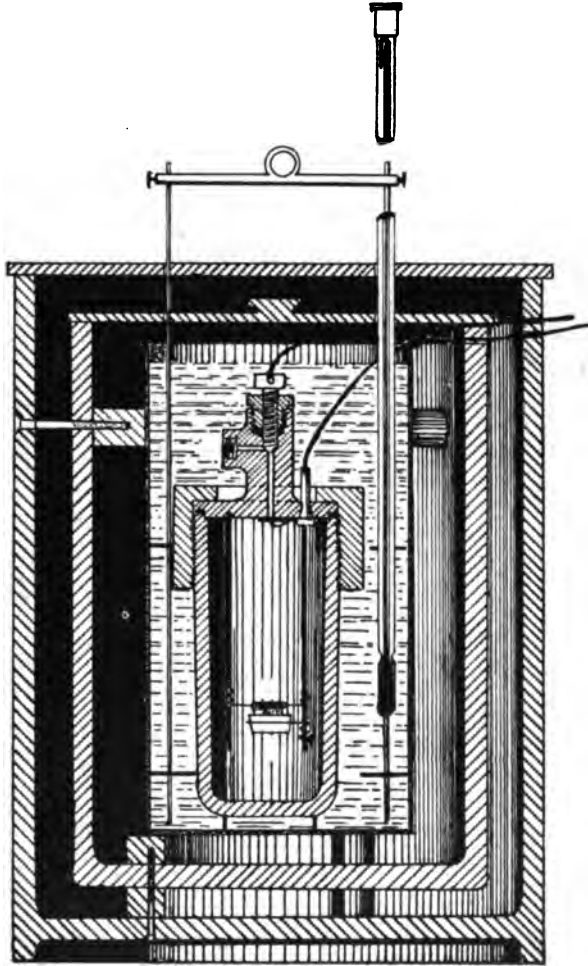


FIG. 69.—CROSS-SECTION THROUGH THE MAHLER CALORIMETER (ATWATER MODIFICATION).

bright and clean to render the thermal losses low and regular.  
The outer envelopes, in the Atwater form, are of indurated

fiber having an air space between the adjacent walls. The covers are of hard rubber, arranged also with an air space and perforated for the stirrer and the thermometer. In some of the other forms this outer envelope is a felt-covered, water-filled metal jacket, but this is not necessary or convenient. Whatever the outer envelopes be, they must not absorb water and they must be easily cleaned and dried for use.

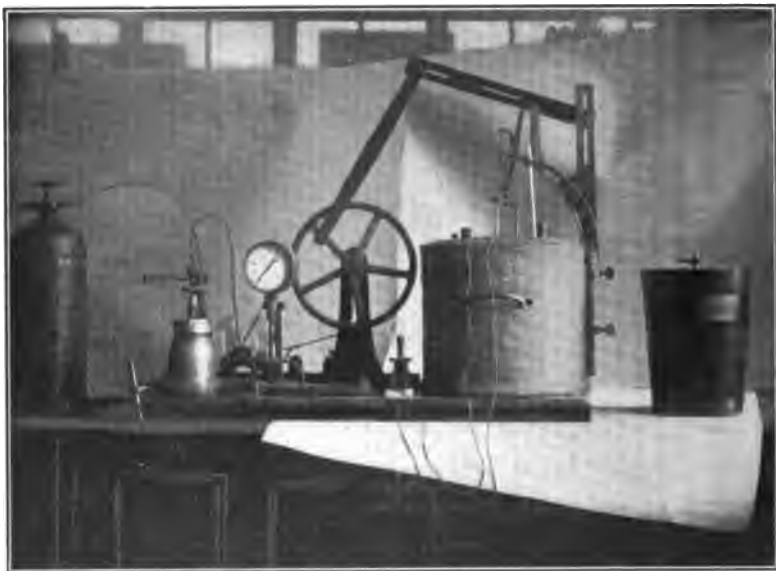


FIG. 70.—BERTHELOT-MAHLER APPARATUS READY FOR OPERATION, IN THE METALLURGICAL LABORATORY OF COLUMBIA UNIVERSITY.

Stirring is effected by the passage of two perforated annular brass rings which encircle the bomb and fit within the calorimeter pail. The up-and-down movement is best brought about by a motor connected by a stout cord or system of levers, as shown in Fig. 70. For this a low-priced motor may be used, as is shown in Fig. 70, instead of the rather expensive type wound for high voltages. Fig. 70 shows the apparatus assembled and the disposition of the different parts.

Most materials are in powdered form on account of the necessity of securing a representative sample, and in such cases it is best to press the powder into a compact pellet, so that small particles may not be blown about within the bomb and escape combustion. This is done in the pellet press *A*, shown in Fig. 71, which is capable of exerting a pressure of about ten tons on the material being bricked. Such a pressure consolidates most sub-

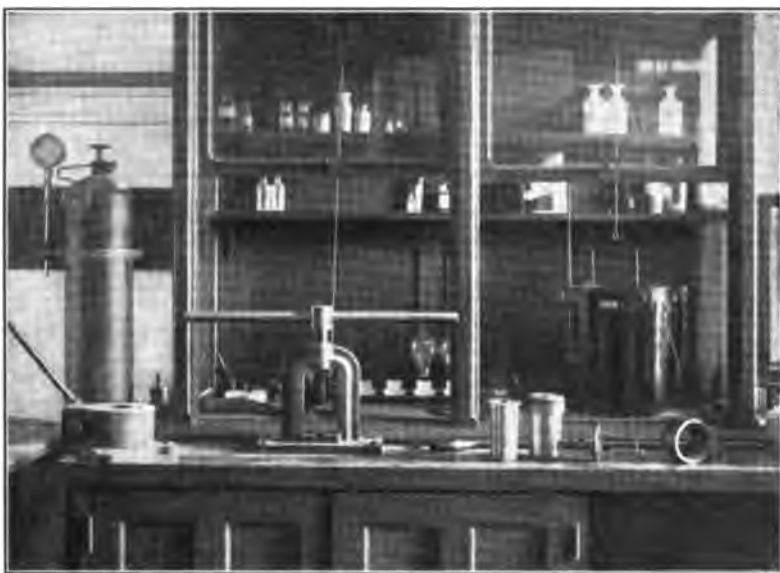


FIG. 71.—VARIOUS PARTS OF THE BERTHELOT-MAHLER CALORIMETER.

stances, but in the case of some anthracite coals, etc., the mixture of a little benzoic acid in known amount will give the desired result. The benzoic acid must be known, that we may make the proper correction by deducting its heat of combustion from the total calories evolved.

**METHOD OF USE OF THE APPARATUS.**—The quantity of substance taken for combustion will vary somewhat with the different forms of apparatus, the rule being that the observed temperature rise

should be 2.5 to 3.5° C. This rise is affected by the hydrothermal value of the calorimeter system, with a large hydrothermal value it being necessary to take a correspondingly large amount of the material to be burned. The hydrothermal values of various calorimeters range from 2000 to 3000 grams, and from this it is clear that such a weight should be taken as will yield 5000 to 7000 calories, or 7500 to 10,500 calories, according to the apparatus. For most good coals, etc., the weight will fall between 1 and 1.5 grams, which should be weighed out approximately and compressed into a solid pellet, which is brushed free from loose particles and weighed accurately in the capsule in which it is to be burned. These capsules are of nickel, about 0.4 mm. ( $\frac{1}{8}$  in.) thick, and of a proper size to fit in the receiving dish of the bomb, which is thereby protected from rapid deterioration. The nickel capsule should be ignited in a Bunsen burner, to superficially oxidize it.

The wire used for ignition should be of soft iron, about 36 gauge and  $2\frac{1}{2}$  to 3 in. in length. To form it into a coil it is wound around a large needle of wire, leaving half an inch of each end straight. Its weight should be known in order to make the correction for its combustion. This is most conveniently done by winding a number of turns about a cylinder of the proper circumference and cutting all at once. With care the weights of these wires should correspond very closely, and thus obviate repeated weighings. One of the coils is bridged between the platinum wires attached to the cap; then the capsule containing the substance is put in place, the wire being brought over it in close contact.

With some substances special devices are required to secure combustion. This is true of refuse, bituminous slates and shales. Ash, etc., the calorific power of which may sometimes be quite high, falls in this class. These substances may be completely burned by mixing with a proper amount of benzoic acid before compressing. This amount should not approach 50% of the total calorific power, and so much should not be used that the remaining cinder is fused by the intensity of the heat generated, for this may prevent complete combustion.

Heavy oils, etc., may be absorbed in fibrous asbestos which has been ignited and weighed in the capsule. The gain in weight after

addition of the oil represents the sample taken for combustion. Volatile oils and liquids should be enclosed in gelatine capsules, the weight of which is known. Trial by combustion of a sample of the capsules will give the proper correction to be applied to each.

Having everything in readiness, the bomb cover is placed on the bomb, which is gripped tightly by the clamp *B*, Fig. 71. The cover is screwed firmly into place by means of the spanner, using oil on the exterior rubbing parts. To fill with oxygen the bomb is taken to the oxygen tank and connected at *O* by a brass tube, the valve *V* being slightly open; the pressure is admitted from the oxygen tank until the pressure-gauge registers 20 atmospheres. The pressure is now cut off and the valve *V* closed. After disconnecting, the bomb is ready for immersion in the calorimeter-pail. It is a wise plan to test the tightness of all joints at a low pressure, say 5 atmospheres. This can be done for large leaks by closing the oxygen-tank valve and noticing whether the pressure-gauge remains constant. More delicate tests for leaks are made by moistening the joint, when bubbles will indicate the exact location. Any perceptible leak about the bomb must be remedied, lest it render the results inaccurate.

The water weighed into the calorimeter-pail should be about 3° below that of the air, in the inner air space. This difference in temperature is such that, under average conditions, the radiation corrections to be applied will be at a minimum. Such a weight of water should be taken that the total hydrothermal value of the system shall be a round number, say 2000, 2500 or 3000 grams. Therefore, the weight of water to be weighed out will be the hydrothermal *equivalent* of the system subtracted from the desired hydrothermal *value*. The weight of the water need only be to the nearest gram.

The calorimeter-pail is now placed in the inner compartment, the stirrer is placed in position, the bomb immersed, with the electrical connections in place, the covers are put on, and finally the thermometer is introduced.

The thermometer used must be one capable of being read to 0.001°, and it should be graduated to hundredths. Either a series of short-range fixed zero thermometers must be provided, or one

of the "metastatic" Beekmann type of adjustable zero. The choice of the latter introduces the necessity for a correction, which cannot be disregarded, depending upon the amount of mercury in the expansion bulb; but it is rather preferable to the series arrangement, and is certainly far less expensive. A reading-lens is necessary for estimating the smaller divisions, and it should be so arranged as to avoid parallax.

Electric current is needed for the ignition, and it is also the most convenient source of power for actuating the stirring mechanism. Rather the best source of current for this purpose is the ordinary lighting circuit, for which the motor driving the stirring apparatus may be wound, or a much cheaper motor intended for battery work may be used in connection with a lamp resistance, and the speed be reduced by a large band-wheel, as is shown in Fig. 70. For ignition, about 5 amperes should be supplied by means of five 32-candlepower incandescent lamps. These also give the signal when the circuit is closed, and ignition takes place by their brightening. In case the lighting current is not available, six Edison-Lalande batteries may be used.

The stirrer may be set in motion at a speed of not less than 40 strokes per minute. A higher speed may be used with advantage, but care must be exercised that it is not so great as to splash the water against the cover, or out of the calorimeter-pail. The thermometer bulb should be slightly over half-way down, or about opposite the central mass of the bomb. It passes through a good-sized opening in the stirrer, and is held firmly by an exterior arm attached to the outer envelope.

When the thermometer shows, by its uniform rise, that the system has attained an equilibrium (this requires 5 or 6 minutes), we are ready to take the observations which compose the initial period. Just before taking the thermometer reading it is a good plan to tap the thermometer lightly with a pencil, so that the surface tension and frictional resistance of the moving mercury may have no effect upon the accuracy of the readings.

*Observations Required.*—We shall require the actual temperature of the system to the nearest half-degree in order to make the correction of the metastatic thermometer, if this is used, due





to the varying quantity of mercury in its bulb. This may be taken with an ordinary thermometer.

For the initial period we need six temperature readings at one-minute intervals. These readings are taken to  $0.001^{\circ}$ , and must show a perfectly uniform rate of rise in temperature. At the moment of the sixth reading—that is, at the expiration of the fifth minute—the switch completing the ignition current is closed. The ignition should take place promptly, with only a momentary brightening of the lamps. The darkening of the lights indicates the breaking of the circuit by ignition of the wire; and this should take not longer than about a second; if it takes a longer time it indicates that the wire is too coarse or the current not strong enough. Short-circuiting may prevent the drop of the lights and the ignition of the charge. Immediately after the ignition has taken place the switch should be opened.

The main or combustion period is now on, and five readings covering the five minutes of the main period are taken by continuing the previous time intervals. During the rapid rise of the temperature it will be impossible to take the readings exactly, but the last three readings may be taken with great exactness, the last especially. The maximum should be attained about the third minute, and it should not be followed by any sudden drop or fluctuation in the indicated temperature, as this points directly to insufficient stirring. Should the rate of fall not become perfectly uniform before the expiration of the main period of five minutes, the period must be extended until it does become so, and the length of time noted for future use in calculation.

Following the main period is a final period of five minutes in length, at the end of which a reading is taken, giving the average rate of fall for use in the calculation of the radiation correction. The bomb can now be removed and secured tightly in the clamp. The internal pressure is relieved by opening the valve *V* gently, and the cap is removed by the use of the spanner. The interior of the bomb and cover are rinsed into a beaker with distilled water. The nitric and sulphuric acids in this are estimated as follows: The solution in the beaker is titrated with a sodium carbonate solution containing 3.706 grams ( $\text{Na}_2\text{CO}_3$ ) per liter, using methyl

orange as an indicator. Each cubic centimeter of this solution equals a calory of heat evolved by the combustion of the corresponding nitrogen. Sulphuric acid is included in this titration, and may be allowed for by precipitation by means of barium chloride. The barium sulphate resulting is weighed and each 0.008 gram equals a calory to be deducted from the nitric-acid estimation.

As the heat of the burning nitrogen has no connection with that of the burning fuel, the heat thus evolved is to be deducted from the total. It usually amounts to from 10 to 30 calories. The heat evolved by the burning sulphur is a portion of the calorific power of the fuel, but its only significance here is that it may lead to a high estimation of the nitric acid. Its equivalent (roughly 0.01 gram barium sulphate equals 1 calory) is to be deducted from that of the nitric acid. It is usually insignificant, but should be looked for in case the nitric acid value seems high.

Any iron wire remaining unoxidized should be weighed or measured, and the proper correction made in the accessory combustions.

**CALCULATION OF RESULTS.**—To find the heat of combustion of the substance burned, it is necessary to ascertain the total heat evolved, and to deduct from the total the heat liberated in the accessory combustions. To find the total heat evolved, we must know the hydrothermal value of the calorimeter system and its corrected rise in temperature. The hydrothermal value of the system is the sum of the weight of water used, and therefore known, and the hydrothermal equivalent of the system. This latter is a constant; later the method of ascertaining its value will be shown. The corrected rise in temperature is found by the application of the laws of radiation to the observations taken.

It is very important that such a form be made out prior to the tests, as confusion and the possibility of error are thereby avoided. The computation, though simple, can become very intricate without some such systematic arrangement.

In this sheet the general data are entered at the top and the records of observation in the left column. No corrected thermometer readings are shown in this example, for the reason that a fixed-zero instrument was used.

The method of calculation is best shown by an example taken from practice, which is shown on the accompanying form.

## CALCULATION 11.

## CALORIMETER TEST

Sample No. 85,544. Temp. Room, 19.5.	Description, Bituminous Coal. Time, 3:20.	Date, Jan. 18, 1904. Temp. Water, 16.7.
---	--	--

---

CAPSULE No. 5	CORRECTION FOR ACCESSORY COMBUSTIONS
---------------	--------------------------------------

Capsule + substance..... = 5.1835 Capsule..... = 4.0005 Substance W..... = 1.1835	Wt. Fe wire, .0325..... = 52. cal. Titre of HNO <sub>3</sub> formed.... = 25. " Correction for accessories... = 77. cal.
---	--

---

	Min.	Readings	Corrected Temp	INITIAL PERIOD	FINAL CALCULATIONS
INITIAL PERIOD	1	= 17.235		Fall..... = .017	$\theta_s$ ..... = 20.347
	2	= 17.237		Rate V..... = .0036	$\theta_o$ ..... = 17.252
	3	= 17.241		Mean $t^\circ, \theta$ = 17.243	$\theta_s - \theta_o$ ..... = 3.095
	4	= 17.245			Rad. Corr..... = .0187
	5	= 17.248			Corr. Rise... = 3.1137
	6 $\theta_o$	= 17.252			" " $\times 3000$
MAIN PERIOD	7 $\theta_s$	= 19.3		$\theta_s$ = 20.347	- Total Heat. = 9341.
	8 $\theta_s$	= 20.31		$\theta_o$ = 17.252	Accessories... = 77.
	9 $\theta_s$	= 20.350		$\theta_s + \theta_o$ = 37.599	Corr. Heat... = 9264.
	10 $\theta_s$	= 20.350	80.310	$\frac{1}{2}$ = 18.799	log. Corr. Heat = 3.96679
	11 $\theta_s$	= 20.47			" W..... = .07362
					Diff. log..... = 3.8937
FINAL PERIOD (5 MINUTES)	$\theta_s + \theta_o$ ..... = 18.799			Antilog. equals 7.832	
	2			CALORIES 7832.	
	Sum..... = 99.109			" $\times 1.8$	
	5 $\theta$ ..... = 86.215				
	Diff..... = 12.894			- B. t. u. 14097.	
	log. diff..... = 1.11050				
	log. V' - V .. = 2.94448				
	log. $\theta' - \theta$ = 1.52073				
	log..... = 1.57571				
	Antilog..... = + .0387				
+ 5 V..... = .0180					
Rad. Corr..... = .0187					
16..... = 20.321					

The correction for radiation is calculated by means of the Regnault-Pfounder formula:

$$C = NV + \frac{V' - V}{\theta' - \theta} \left( \frac{O_s + O_e}{2} + \sum_{\theta}^{n-1} \frac{1}{\theta - N\theta} \right)$$

Where  $N$  = number of time units (minutes) in combustion period.

$V$  = rate of fall of temperature of calorimeter during initial period.

$V'$  = rate of fall of temperature of calorimeter during final period.

$\theta$  = mean temperature of calorimeter during initial period.

$\theta_1$  = mean temperature of calorimeter during final period.

$O_1, O_2, \dots, O_n$  = temperature at the end of first, second  
...nth minutes of the combustion period.

$\theta$  = temperature at moment of ignition.

Applying this formula to the example given, we find that the first reduction of the observations is made in the second column. This being completed, a summation of the first four observations, in the main period, is made in the left column (80.310). This is combined with the other expressions within the bracket by transferring their values from the center column. Logarithms are used to effect the reduction with the fractional form, and the final reduction is also assisted in the same manner. The radiation correction is added to the difference between the final ( $\theta'_s$ ) and initial ( $\theta_e$ ) temperature of the main period. This gives the corrected rise, which, multiplied by the hydrothermal value of the system, will give the total heat evolved. From the total heat we subtract that due to the accessory combustions, and this corrected heat, divided by the weight of the sample, is the calorific power of the substance, expressed in calories per gram. It is usual to give the value of a fuel also in British thermal units, which is done by multiplying the calorific power by 1.8.

The correction for accessory combustions is made in a very simple manner from the known weight and heat of combustion. Thus, in the example, the weight of the iron wire used was 0.0325 gram, and this, times the specific heat of combustion, gives the calories (52) to be deducted.

The following specific heats of combustion are accurately known:

Pure iron or soft iron wire,	1601	calories	per	gram.
Naphthalene .....	9628	"	"	"
Cane-sugar .....	3959	"	"	"
Benzoic acid .....	6322	"	"	"

*The Hydrothermal Equivalent.*—This constant is usually furnished with the instrument, but in case of change of parts or loss of its recorded value it may be easily found by burning a known weight of a standard substance, such as benzoic acid, the heat of combustion of which is very accurately known.

The following quantities are involved, and the relation is expressed by the formula

$$H = (W + X) T$$

Where H = the total heat liberated,

W = the weight of water used,

T = corrected temperature rise,

X = the desired hydrothermal equivalent.

H, the total heat, is found from the weight and heat of combustion of the standard substance used plus the heat derived from the accessory combustions, including nitric acid and the iron wire, etc.

**ACCURACY OF THE METHOD.**—The actual accuracy attained will largely depend upon the care and expertness of the operator. Conditions outside the operator's control may considerably affect the accuracy attainable. Violent draughts of air, changing temperature of the room, dampness of the interior chamber, or looseness of covers by which currents of air may pass through the interior chambers, are sources of error. The chief source of error lies in the temperature observations, and it follows that these must be very carefully made.

With care and reasonably good conditions the total error of estimation should not be greater than 0.5%, and greater deviations should be cause for repetition or investigation of the apparatus.

The time required to make an estimation with a compact and

conveniently arranged apparatus should not exceed 40 minutes, and with a systematic arrangement the time may be much shortened.

#### THE PARR CALORIMETER.

This calorimeter is a modification of the Thompson form, in that it uses the oxidizing power of chemicals to effect the combustion of the fuel. It avoids one of the serious sources of error of the latter by the use of sodium peroxide, which, in decomposing, oxidizes the fuel and at the same time absorbs the products of combustion so that they do not escape through the surrounding water.

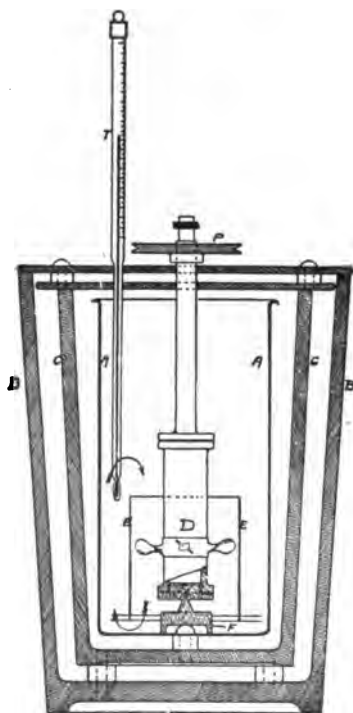


FIG. 72.—PARR CALORIMETER.

The exterior jacket is not unlike the outer envelope of the At-water-Berthelot calorimeter. The bomb is replaced with a small chamber, *D*, capable of revolution about a vertical axis. A proper weight (0.5 to 1 gram of the fuel) mixed with 16 to 32 grams of sodium peroxide and the accessory chemicals is placed within this chamber and the cap is fitted on tightly. It is then immersed in the calorimeter-pail containing 2000 cc. of water. Stirring is effected by the propeller wings fastened to the rotating chamber; a speed of about 150 revolutions is recommended. When equilibrium is reached, as shown by the thermometer, the charge is ignited by means of a red-hot wire introduced through the valve-stem. Ignition takes place with rise of temperature. The observations to be made can be recorded exactly, as those outlined for the bomb calorimeter, or the directions given with the apparatus may be followed.

The same precautions apply to this calorimetric measurement as to others, and in addition the mixture between the fuel and the peroxide must be thorough, and both should be finely powdered, the fuel to 100-mesh and the peroxide to 50-mesh. The operator should tap the cylinder gently on the bottom, so that all the contained material shall gather there, for any adhering to the sides or about the valve will escape combustion. Dampness must be carefully avoided, as it is likely to ignite the charge and ruin the determination.

With anthracite and some other substances not readily combustible it is necessary to add an accelerator to the charge. This is composed of tartaric acid 33% and potassium persulphate 66%. Even with a liberal addition of this mixture the combustion is not always complete. One and one-half grams of this mixture is used, with 12 grams of sodium peroxide, for the combustion of 0.5 gram of coal.

The corrections needed are: (1) For radiation losses. These are made exactly as in the bomb calorimeter, though the printed directions from the makers do not mention this point. Reliance is placed in exactly balancing the loss and gain by starting at a sufficiently low temperature, that recommended being 3° F. below room temperature. Experience with any calorimeter shows that this

is rarely the case, and it will not do to ignore this point. (2) Corrections due to auxiliary chemical reactions, aside from the union of the oxygen with the fuel. These consist of (a) the decomposition of  $\text{Na}_2\text{O}_2$ , forming  $\text{Na}_2\text{O} + \text{O}$ ; (b) the union of sodium oxide with carbon dioxide,  $\text{Na}_2\text{O} \times \text{CO}_2 = \text{Na}_2\text{CO}_3$ ; (c) the union of sodium oxide and water,  $\text{Na}_2\text{O} + \text{H}_2\text{O} = 2\text{NaOH}$ ; (d) the decomposition of sodium peroxide by water,  $\text{Na}_2\text{O}_2 + \text{H}_2\text{O} = 2\text{NaOH} + \text{O}$ . If the accelerator is used, the following also enter, namely: (e) Decomposition of the potassium persulphate into potassium sulphate, oxygen and sulphuric anhydride, with the subsequent formation of sodium sulphate due to the presence of sodium hydroxide; (f) the combustion of the tartaric acid, with its attendant series of reactions.

The first four of these are corrected by the use of an arbitrary factor which has been found by experiment to be within about 1% of the truth. This factor amounts to the deduction of 27% of the heat evolved *after making all other corrections*. Corrections for (e) and (f) are made by running a charge consisting of 0.5 gram of tartaric acid, 1 gram of persulphate and 6 grams of peroxide. The calories evolved are to be corrected for the iron wire and deducted from like combustions with the accelerator.

The makers give the tartaric acid equivalent as 1779 B. t. u. (988 calories) and the persulphate equivalent as 330 B. t. u. (183 calories). The iron wire equivalent (wt. of iron being 0.4 gram, its temperature  $700^\circ\text{F}$ ., and sp. ht. 0.114) is  $0.4 \times 700 \times 0.114 = 31.9$  B. t. u. (18 calories). This rather crude approximation probably gives results within the limits of accuracy of the apparatus.

(3) A deduction is made for the estimated heat carried by the hot wire used for ignition. The temperature of this wire will vary from  $700^\circ$  to  $1200^\circ\text{F}$ . ( $389^\circ$ – $667^\circ\text{C}$ .) above the room temperature. The temperature difference, times the specific heat, times the weight of the wire gives the correction.

The specific heat of soft iron is from 0.111 to 0.114.

“ “ “ copper “ 0.092.

From the observations made, a computation parallel to that shown



in full for the bomb is made, or, when accuracy is not required, the directions accompanying the apparatus may be followed, and for this purpose they are here given.

#### DIRECTIONS FOR USING THE PARR STANDARD CALORIMETER.

The calorimeter should be placed on a good firm desk or table. The power needed is exceedingly slight, the smallest electric or water motor being ample. Revolve the pulley by means of a loose cord at the rate of about 150 r. p. m.

The general arrangement of the parts is shown in Fig. 72. However, the can should be removed from the instrument for filling with water, and care observed that no water remains on the outside or is allowed to spill over into the air spaces of the insulating vessels. Exactly two liters of water (preferably distilled) are used, and it should have a temperature about 3° F. (1.65° C.) below that of the room. That is, approximately three-fourths ( $\frac{3}{4}$ ) of the total rise in temperature should occur before the temperature of the room is reached.

The glass jar is for the chemical, and should be kept carefully closed and clamped to prevent absorption of moisture from the air. For this reason, also, the contents of only one small can of chemical is emptied into the jar at one time. There must be also room left for the measuring-cup and handle entire.

The cartridge for filling should be perfectly dry inside and out. If water has been admitted to the valve, remove it from the stem by screwing off the knurled top and drying all parts thoroughly. To prepare the cartridge for filling, screw on the bottom firmly so as to avoid any possibility of admitting water to the interior, then place on a sheet of white paper.

The coal is prepared by grinding in a mortar and passing through the sieve of 0.25 mm. mesh, or 100 to the inch. Coals containing over 2.5-3% of water should have the water removed. In such cases the exact charge of the commercially dry coal is weighed out and dried for an hour at 105°-110° C. (220°-230° F.), then transferred to the cartridge.

PROCEDURE FOR ALL ORDINARY SOFT COALS.—(Not anthracitic

or true anthracites.) Exactly  $\frac{1}{2}$  gram is taken and dried as above indicated.

One full measure of chemical is put in the cartridge and the coal added. Screw on the top with valve or loop of fine wire for electrical ignition, and shake vigorously to thoroughly mix the contents. In shaking the cartridge it is well to hold the thumb against the valve-stem (at *E*, Fig. 72) to prevent its opening and admitting the material into the stem. When the mixing is complete, tap the cartridge lightly to settle the contents and to shake all the material from the upper part of the cylinder. Tap the valve, also, to see that it works freely. Put on the spring clips with vanes. The cartridge is now put in place, the can with water being already in position. Adjust the cover. Insert the thermometer so that the lower end of the bulb will be about midway towards the bottom of the can, place the pulley on the stem and connect with the motor. The cartridge should turn to the right, or as the hands of a watch, thus deflecting the currents downward.

After about three minutes the first reading of the thermometer may be taken.

Ignite with the short piece of iron wire which is held or rests on a wire gauze in a Bunsen flame till red hot; drop quickly into the opening at the upper end of the valve. With the pinchers the valve is now pressed completely down and released with a quick motion, so as to prevent the escape of heated air from the interior.

All the time, of course, the revolving of the cartridge continues. The combustion should be indicated by a rapid rise of the mercury, which reaches its maximum height after from four to five minutes. Make note of the final temperature, and compute thus:

*Calculation.*—Subtract the correction factor for the heat of the wire—namely,  $0.022^{\circ}$  F. ( $0.0122^{\circ}$  C.)—and multiply the remainder by 3110. The product will be the number of British thermal units per pound of coal. Where the electric method of ignition is used this correction for the wire may be disregarded.

To dismantle, remove the thermometer, pulley and cover; then take out the can and contents entire, so that the lifting out of the cartridge will not drip water into the dry parts of the instrument.

Remove the spring slips and unscrew the ends. Place the cartridge in a dish of hot water. The contents will dissolve out quickly. The cartridge and ends should be at once thoroughly dried, when they will be ready for a new test.

*Note.*—(a) With the electric method of ignition the fine wire is wrapped firmly, with good contact, around the ends of the terminals, and bent U-shaped so as to extend below about half an inch. Do not have too great a length of wire for the current. Make a preliminary test without screwing the stem into the bomb, so that the action can be seen. The wire should quickly become incandescent. (b) Lignites and fuels of low calorific content may be too greatly diluted in the above ratio of material for perfect combustion. In such cases weigh out *one* gram and dry. Take  $1\frac{1}{2}$  measure of chemical. The factor for computing will be 1555 instead of 3110.

FOR ALL ANTHRACITES AND ANTHRACITIC SOFT COALS, COKES, ETC.—Grind and sift the coal as usual. Weigh out exactly  $\frac{1}{2}$  gram for the test; drying may be omitted if the water content is below  $2\frac{1}{2}$  or 3%. Transfer the sample to the cartridge and add exactly  $1\frac{1}{2}$  grams of the “special chemical” for anthracites, petroleum, etc. Then add *one and one-quarter measure* of the ordinary chemical. Shake thoroughly, place in the can, assemble and complete the combustion in the usual manner.

The correction factor for the special chemical and hot wire is marked on the label. Subtract this number from the total rise in temperature and compute thus: Multiply the remainder by 3110. The product will be the British thermal units per pound of fuel.

FOR PETROLEUM, ETC.—Proceed exactly as for anthracites. Prepare a small, light, 15 c.c. weighing-flask with perforated cork and dropping-tube, with common rubber-bulb cap. Fill the flask about  $\frac{3}{4}$  full of oil and weigh carefully. Place in the cartridge  $\frac{1}{2}$  measure of chemical and  $1\frac{1}{2}$  grams exactly weighed out of the “special chemical.” Then, by means of the dropping-tube, add about 0.300 gram (25–30 drops) of oil. Stir the mixture in the cartridge thoroughly with a piece of wire. Add the remainder—that is, one measure of ordinary chemical. Remove the wire,

cleaning it as well as may be in this upper layer and without jarring off any particles. Screw on the cap, shake well, place in the calorimeter and ignite as usual. Weigh back the flask carefully and determine the amount of oil taken by difference. Compute by formula instead of using the factor, thus: Correcting as before for the wire and extra chemical employed, letting "r" equal the corrected rise in temperature; then 
$$\frac{"r" \times .73 \times 2130.}{\text{wt. of oil.}} = \text{British thermal units per pound of oil.}$$

## NOTES.

(a) The factor 3110 is deducted as follows: The water used, plus the water equivalent of the metal in the instrument, amounts to 2130 grams. In the reaction 73% of the heat is due to combustion of the coal and 27% is due to the heat of combination of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  with the chemical. If, now,  $\frac{1}{2}$  gram of coal causes 2130 grams of water to rise "r" degrees, and if only 73% of this is due to combustion, then  $73 \times 2130 \times 3 \times "r"$  equals rise in temperature that would result from combustion of an equal weight (2130 grams) of coal— $73 \times 2130 \times 2$ —equals 3110. Where 1 gram of coal is taken this factor, of course, becomes 1555.

(b) The ignition wire is of soft iron  $2\frac{1}{2}$  mm. in diameter, or No. 11 gauge, and 1 cm. long. It should weigh approximately 0.330 gram. It looses very little by use. When by oxidation the weight falls much below 0.300 gram a new wire should be substituted. The correction for the wire may be calculated thus: Taking 0.114 as the specific heat and  $1200^\circ$ – $1300^\circ$  F. ( $667^\circ$ – $723^\circ$  C.) as the temperature at a red heat. Then 
$$\frac{1250^\circ \times .330 \times .114}{2130} = 0.022^\circ \text{ (0.0122}^\circ$$

C.). This agrees closely, also, with the factor obtained experimentally. A variation of a hundred degrees in the initial temperature of the wire causes a difference in the final reading of only  $0.002^\circ$  F., or six thermal units, and may be disregarded.

(c) Chemicals vary, moreover the sodium peroxide may have become contaminated with moisture from the air. It is advisable,

if question arises, to run a blank thus: Weigh out  $1\frac{1}{2}$  grams of the "special chemical" mixture of tartaric acid and potassium persulphate, place in the cartridge, add also one measure of the ordinary chemical sodium peroxide; shake and ignite in the usual manner. Duplicates should agree closely with each other and with the standardized factor marked on the label.

(d) Do not bring the instrument from a cold room to work at once in a warm room, or *vice versa*. An hour, at least, should be given for equalization of temperature.

(e) Do not throw a mixture of chemical and unburned coal into water. It may ignite violently. Similarly, a drop of water left inside of the valve may work into the charge during the shaking and ignite it prematurely.

(f) It is well to test the action of the valve by dropping the wire through on to a sheet of paper a number of times, holding the stem in the hand and dropping the wire as in igniting a charge. It will be noted that the wire is allowed to lodge at the valve and then is released by pressure on the top. Too sudden a pressure and release, or a failure to press the valve completely down, may result in catching the wire before it has cleared the valve. In such a case, of course, the charge would fail of ignition.

(g) The above directions presume the use of a Fahrenheit thermometer. In case a centigrade thermometer is used, the use of the factor 3110 gives the result in kilocalories. To change kilocalories to British thermal units, multiply by 1.8. Also the correction factors as herein given should be divided by 1.8. Thus, for the hot wire the correction would be  $0.012^{\circ}\text{C}$ .

(h) A piece of fine emery cloth around the cartridge will facilitate holding the same when unscrewing the ends.

The advantages of the Parr calorimeter over the bomb are its independence of compressed oxygen and its lower price. The possible error is much greater than that of the bomb, though duplicates may check very closely. The inaccuracy due to temperature readings on the thermometer furnished (divided to  $\frac{1}{2}^{\circ}$ ) may amount to over 1% and the error of estimation of the correction of the hot wire may be 0.1%.

A liberable estimate of the probable error will be from 1 to 2%.

The time taken for an estimation is about the same as that for the bomb.

#### JUNKER'S CALORIMETER.

The principle upon which Junker's calorimeter (for gas and oils) depends is that of burning the substance with a free access of air, and passing the products of combustion through a cooling chamber. The thoroughly cooled gases are discharged into the atmosphere, and the rise in temperature of the cooling medium affords the measure of the heat evolved.

It is readily seen that this is very similar to industrial heating, and in fact the Junker's calorimeter is simply a small tubular boiler of relatively large heating area. Fig. 73 shows the calorimeter proper in section plan and elevation. It will be seen that the gases of combustion ascend to 29, where they are directed downward through the water-cooled tubes, 30, and finally emerge, fully cooled, through exit, 32, to the atmosphere. The cooling-water enters at 1, part of it overflowing at 5, the constant-head device; the feed-water descends in tube, 3, to the valve, 9, and thermometer, 12, whence it enters the calorimeter chamber at 13, and is distributed by a perforated annular sheet, 14. The water gradually rises through the mixers, 17, past the thermometer, 43, and is discharged without suction over the funnel lip, 20.

To maintain a constant and measurable supply of gas to the calorimeter, a very delicate pressure regulator and a gas meter divided to 0.001 liter are needed. A U-tube pressure gauge should also be used to read the pressure under which the meter is working. The thermometers used for measuring the temperature of the inflowing and outflowing water are divided to  $\frac{1}{10}^{\circ}$ , and have a range from 0 to 50°. The temperature of the air and exit gases is taken with an ordinary thermometer.

*Apparatus Arranged for Use.*—For use the calorimeter and adjuncts should be arranged as follows: To the gas main or supply attach the pressure regulator, and to this connect the gas meter. Between the meter and the calorimeter burner is inserted the U-tube pressure gauge charged with water, colored if desired. The



FIG. 78.—JUNKER GAS CALORIMETER.

Bunsen burner to which the tube from the meter is attached must afford complete combustion of the gas. The water-supply tube is attached to the faucet, and the two overflow pipes run to a waste-pipe which must be close by.

*Starting the Calorimeter.*—Water is turned on of sufficient volume to overflow continually through tube, 5, the valve, 9, being sufficiently open to allow a flow of, say, 200 c.c. per minute through the calorimeter. Note that no drip of water takes place from tube, 35, as this would indicate a leak in the cooling chamber. Being satisfied as to this point, a glass graduate is placed here to catch the condensed water of combustion.

Gas is turned on from the main, the Bunsen-burner valve, 22, being closed. The needle of the gas meter should become stationary and remain so, otherwise a leak of gas is indicated beyond the meter, and this must be remedied. Everything being in proper condition, the Bunsen burner is taken out and lighted, such a regulation being given that the flame evolves about 1000 to 1200 calories per hour; this will represent a gas consumption in the case of—

Illuminating gas.....	100 to	400	liters per hour.
Hydrogen.....	200	“ 800	“ “ “
Water-gas.....	300	“ 1000	“ “ “
Mixed gas.....	400	“ 1600	“ “ “
Producer-gas.....	500	“ 2000	“ “ “

After replacing the burner, the flame of which must not come below the water-jacketed level, a few minutes are allowed for the heating to take effect, and then adjustments in the rate of flow of the water are made, such that the exit gases are cooled practically to room temperature, and the rise in temperature of the water is about 10° C. This rise should be equally distributed on each side of the room temperature—that is, the feed-water should be as much below that of the room as the exit-water is above. Error from radiation is then at a minimum, but this condition cannot always be had. Corrections for radiation cannot well be made, on account of the gradual change in temperature from



top to bottom, and therefore this loss should be kept as low as possible.

The damper for the exit gases should not be shut off so much as to cause hot air to escape through the air inlets, and likewise draughts should be avoided, as they may cause back currents. The gas pressure should be recorded, and it should remain perfectly constant.

*Taking Observations.*—Testing gas.—A few minutes must be allowed for the attainment of equilibrium and the steady reading of the thermometers registering inflowing and exit water, also the exit gas.

The following observations are to be taken:

W, the amount of exit water flowing during the time of burning.

G, the amount of gas burned.

T<sub>1</sub>, temperature of inflowing water to 0.01 C.

T<sub>2</sub>, " exit water " "

T<sub>3</sub>, " room or gas.

T<sub>4</sub>, " exit gas.

P<sub>1</sub>, pressure of gas to burner in mm. mercury.

P<sub>2</sub>, barometric pressure of the atmosphere.

When the temperature becomes steady the tube carrying the exit water is changed, exactly as the meter needle crosses zero, to a weighed receiving dish. Record of T<sub>1</sub> and T<sub>2</sub> is now taken at equal intervals of time, frequent enough to bar the possibility of an unnoticed change. T<sub>3</sub>, T<sub>4</sub>, P<sub>1</sub> and P<sub>2</sub> can be taken at once and should not vary, though it is well to check T<sub>4</sub>.

Exactly as the meter needle crosses the determined volume to be burned, say 3 liters, the exit tube is replaced in the waste-pipe and the receiving dish is weighed. The gain in weight is W. Record is also taken of the water of condensation which has collected during the same time as W.

*Testing oils.*—In testing oils and inflammable liquids the general procedure is the same as above, the only variation being in the manner of estimating the amount of material burned.

The liquid is burned in a lamp, which first volatilizes it and then burns the gas, as is done in the Turner gasoline-blast lamp. Supply of liquid and pressure is insured by compressing air in a chamber above the liquid. To light this lamp it must be pre-heated, either by a Bunsen flame or by benzine ignited in a receiving cup for this purpose. When lighted the lamp is placed on a balance, similar to the standard-candle balance, and brought to position in the calorimeter. When the condition of constant temperature is reached, the balance is brought nearly to equilibrium. The loss of weight, due to burning, will soon cause the pointer to move past the zero point; at this moment the test begins. The tube is then transferred to the weighing vessel and the observations taken. A weight representing the quantity of substance it is desired to burn is taken from the balance; the equilibrium thus destroyed will be regained by loss in burning, and when this occurs the test ends, just as in the case of testing gas. The total heat generated,  $W \times R$ , divided by the weight of liquid burned, will give the calorific power per unit weight.

*Calculation.*—The formula  $\frac{W \times R}{G} = H$ , where  $H$  is the calorific

power per unit (volume or weight) and  $G$  is this volume or weight burned, is applicable direct in the case of liquids, but gases, on account of the effect of pressure and temperature on volume, must be reduced to standard conditions. For this purpose we employ

the formula  $G_0 = \frac{P \times G \times 273}{760 \times T}$ , where

$G_0$  = volume at ( $0^\circ$  C. and 760 mm.

$P$  = observed pressure of gas supply  $P_1 + P_2$ .

$G$  = volume of gas indicated by meter at  $T$ .

$T$  = absolute temperature of gas =  $T_s + 273$ .

For standard conditions, then,  $M = \frac{W \times R}{G_0}$ . The calculation

and application of this formula are rendered clear by the accompanying example.

## CALORIFIC POWER OF GAS.

$$G = 3.000 \text{ liter.}$$

$$P_1 = 2.4 \text{ mm.}$$

$$P_2 = 748. \text{ mm.}$$

$$\underline{750.4 \text{ mm.}} = P_1 + P_2 - P.$$

$$T_1 = 17.63 \text{ deg.}$$

$$T_2 \text{ 1st, } 26.80 \text{ "}$$

$$2\text{d, } 26.74 \text{ "}$$

$$3\text{d, } 26.73 \text{ "}$$

$$4\text{th, } 26.73 \text{ "}$$

$$5\text{th, } 26.75 \text{ "}$$

$$6\text{th, } 26.77 \text{ "}$$

$$\text{Mean } T_2, \quad 26.753 \text{ deg.} \quad 26.753 - 17.63 = 9.123 = R.$$

$$T_3 = 22. \quad 22 + 273 = T.$$

$$T_4 = 22.$$

$$W = 1.823 \text{ liter,} \quad W \times R = 16.6312$$

$$G_o = \frac{P \times G \times 273}{760 \times T} = \frac{750.4 \times 3.0000 \times 273.}{760 (22. + 273.)} = 2.74 \text{ liter.}$$

$$H = \frac{16.6312}{2.82} = 5.897 \text{ calories per liter.}$$

$$\text{Calorific power per cubic meter} = 5.897 \times 1000 = 5897. \text{ cal.}$$

The use of a wet meter, and often a wet-pressure regulator, results in the delivery of gas saturated with water vapor. This usually is not of importance, as the gas in the mains is already saturated, but should a dry gas be furnished or results be called for on a dry basis, a correction depending upon temperature and pressure will have to be made.

*Accuracy of the Instrument.*—With care as to details the Junker calorimeter is an accurate instrument. Its main source of error is in the lack of an exact radiation correction, but this may be partly

avoided by the precautions previously mentioned. The accuracy with which the thermometers may be read controls the total rise,  $R$ , and hence the amount of water,  $W$ . With delicate thermometers the value of  $R$  may be so controlled as to nearly eliminate the radiation loss, but less sensitive thermometers necessitate a large value for  $R$ , that the error of reading be not too great, and this involves a corresponding increase in the radiation loss.

*The Low Thermal Value.*—Most uses to which fuels are put do not presuppose the cooling of the products of combustion to ordinary temperatures, or even to the boiling point of water, and hence the latent heat of condensation of the water vapor present, as well as the sensible heat of the gases, is not utilized. Ordinary calorimetric measurements include this inefficient heat, which should be deducted, according to the particular use intended, in order to give relative practical values. The sensible heat lost should be low, and as it varies with each case no general correction is possible, but the latent heat of the water vapor may be 10% of the calorific power, and it should be deducted, the amount depending upon the analysis of the fuel. Its value is readily calculated, knowing the amount of hydrogen present.

This corrected value is known as the *low thermal value*.

#### APPROXIMATE DETERMINATION OF THE CALORIFIC POWER OF A FUEL BY MEANS OF THE MAHLER AND GOUTAL FORMULAS.

Few industrial laboratories are equipped with calorimeters, and it is very often useful to be able to find, within 1%, the approximate calorific power of a fuel. A number of formulas have been proposed for the calculations of the calorific power from the ultimate analysis or the approximate analysis of the fuel. Among them may be mentioned the Vivien, von Jüptner, Goutal and Mahler formulas.

The only two that have stood the test of practice are the Goutal and the Mahler. Fortunately they complete each other. The Goutal makes use of the data obtained from an ordinary proximate analysis, the Mahler of the ultimate analysis.

*Mahler Formula.*—Calorific Power =  $Q'_0$ ,

$$Q'_0 = \frac{8140 C + 34500 H - 3000 (O + N)}{100}$$

This is further simplified if we write

$$O + N = 100 - (C + H)$$

Substituting in the equation, we have finally

$$Q'_0 = 111.40 C + 375 H - 3000$$

in calories per kilogram of fuel.

The comparison of columns 10 and 11 in table 22 shows how closely the computed results agree with the experimental determinations. The formula does not give accurate results in case of cannel, lignites, peat and woods.

*Goutal Formula.*—The data required are the following:

- C Fixed Carbon.
- V Volatile matter.
- a A variable factor.

"a" is a function of the volatile matter of the fuel, abstraction being made of the moisture and ash.

$$\text{Calorific Power} = 82 C + aV$$

For all fuels with volatile matter V' below 40%, the values of "a" are given in table 12.

*Moisture Determination.*—The moisture is determined on a 2-gram sample heated for an hour in an air bath at 115° C. The constant weight should be verified by two weighings.

*Volatile Matter.*—In a crucible of 30 c.c. capacity are placed 5 grams of the powdered fuel; the crucible is placed uncovered over a Berzelius burner. The flame is to be maintained so as to surround completely the crucible. After all the illuminants have been entirely driven off, the heating should be continued for three more minutes.

*Ash.*—Two grams of the fuel are burned in a muffle, the heating to be done very carefully and not too suddenly.

Example.—The analysis of the anthracitic coal of Le Creusot is the following:

Fixed carbon.....	86.70% = C
Volatile matter.....	10.05 = V
Ash.....	1.45
Moisture.....	1.80

The volatile matter  $V'$ , calculated as if there was neither ash or moisture, is

$$V' = \frac{V \times 100}{C + V} = \frac{10.05 \times 100}{86.70 + 10.5} = 10.4$$

TABLE 12.  
GOUTAL FACTORS.

$V'$	a	$V'$	a
%	Calories	%	Calories
1 to 5	100	23	105
5	145	24	104
6	142	25	103
7	139	26	102
8	136	27	101
9	133	28	100
10	130	29	99
11	127	30	98
12	124	31	97
13	122	32	97
14	120	33	96
15	117	34	95
16	115	35	94
17	113	36	91
18	112	37	88
19	110	38	85
20	109	39	82
21	108	40	80
22	107		

From table 12 we find that it corresponds to a value of "a" equal to 129 calories.

Substituting in the formula, we have

$$\text{Calorific Power} = 82 \times 86.7 + 129 \times 10.05 = 8406 \text{ calories.}$$

By actual determination of the calorific power by means of the Mahler bomb it was found to be 8404 calories. The results obtained are generally within 1% of the experimental determinations; an error of 2% is quite exceptional and is observed only with the anthracites or lignites.

## CHAPTER XIV.

### ELEMENTARY FUEL ANALYSIS—THE ULTIMATE ANALYSIS OF FUELS, COAL, COKE, ETC.

*Determination of Carbon, Hydrogen and Ash.*—These determinations may be made in a single combustion. The apparatus used is an ordinary combustion furnace, the variations being that either a porcelain or a wrought-iron tube may be used, and that lead chromate is used in addition to cupric oxide.

All material used in charging the tube, and the tube itself, must be freed from moisture previous to the combustion, by thorough ignition with the passage of a current of dry air. The tube is charged in the central portion, for about 15 c.m., with coarse, strongly ignited cupric oxide; the forward end contains a sheet-iron boat, 20 c.m. long, charged with powdered lead chromate, to retain sulphur, mixed with coarse pumice. In case a wrought-iron tube is used in place of the porcelain, it should be strongly ignited, previous to charging, and steam passed through it. This oxidizes the inside and destroys the porosity of the untreated iron.

The absorption train consists of a U-tube filled with fragments of pumice, wet with strong sulphuric acid, a second U-tube of calcium chloride, a U-tube charged with active soda-lime, a U-tube of sulphuric acid and pumice, and a second U-tube of sulphuric acid and pumice to act as a guard-tube. The entrance train is composed of a soda-lime tube and a sulphuric acid pumice U-tube. *The same drying agent should be used at each end.*

The apparatus should be tested, by ignition and passage of air, until satisfactory constant weights are obtained for the sulphuric-acid absorption tube and the (3) calcium chloride, soda-lime and sulphuric-acid tubes weighed collectively.

To make the combustion, allow the furnace to cool and introduce a weighed porcelain boat, containing 0.5 to 1 gram of the

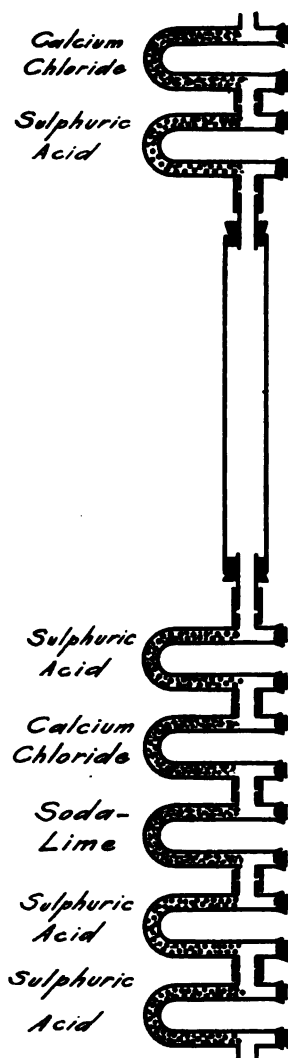


FIG. 74.—TRAIN OF APPARATUS FOR THE ELEMENTARY ANALYSIS OF FUELS.



fuel sample, dried at 104–107° C. The boat should rest on a sheet of platinum foil. The tube is now closed and the burners under the lead chromate and cupric oxide lighted. The lead chromate should be kept at a red heat and the cupric oxide at a bright red heat. When the rest of the tube is properly heated the burners under the boat may be lighted, and it gradually brought to a bright red. The air current should be drawn through the tube at such a rate that about two bubbles per second pass through the sulphuric acid. The combustion should be complete in 30 minutes and the boat can be drawn, cooled and weighed. Its gain in weight, plus  $\frac{1}{8}$  the sulphur content, equals the mineral matter in the coal. Its direct gain in weight is the ash.

The gain in weight of the sulphuric-acid tube equals the water produced and absorbed, which is converted into hydrogen by 0.1119. It is not necessary to take the weight of the calcium chloride tube unless back-suction has taken place. The gain in weight of the three tubes is the carbon dioxide absorbed, and this is converted into carbon by 0.27273.

These results must be converted to the basis of the air-dried sample, using the percentage of moisture found.

*Determination of Moisture.*—Dry one gram of the sample in an open dish in an air bath, at 104–107° C., for one hour. Cool in a desiccator and weigh quickly. The loss in weight is the moisture present.

*Determination of the Sulphur.*—Eschka's method modified according to Miller. One gram of the finely pulverized coal is mixed with one gram of light magnesium oxide and 0.5 gram of anhydrous sodium carbonate, in a platinum dish having a capacity of 75 to 100 c.c., or a Meissen porcelain crucible, and heated with an alcohol lamp. When great accuracy is not required a gas flame may be used, the dish being protected, as far as possible, from the products of combustion which contain sulphur. The mixture is stirred frequently with a stout platinum wire or glass rod, and the heat applied gradually, especially with soft coals, until strong glowing has ceased; then the heat is increased until in fifteen minutes the bottom of the dish is at a low red heat, which is maintained until all of the carbon is burned out. The residue, which should be

nearly white and porous, is transferred to a No. 2 beaker with about 50 c.c. of water; 15 c.c. of bromine water are added, and the whole boiled for at least 5 minutes, allowed to settle, and decanted through a filter; boiled a second and third time with 30 c.c. of water, and then washed very thoroughly with hot water.

The filtrate is acidified with hydrochloric acid so as to have an excess of about 1 c.c. and boiled to expel any free bromine. Then to the hot solution barium chloride (10%) solution is added, drop by drop, until 10 c.c. have been added, and the solution boiled or heated on a water bath until the precipitate settles quickly; filter, ignite and weigh.

From the weight of barium sulphate the percentage of sulphur is calculated. Factor, 0.13736.

*Determination of Nitrogen.*—Kjeldahl's method. Place 1 to 1½ grams of the fuel in a long narrow-necked flask, preferably made of Jena hard glass, of about 150 c.c. capacity, and add 20 c.c. of concentrated sulphuric acid. Add 0.5 gram of phosphorus pentoxide and place the flask in an inclined position over a flame. Heat the contents to boiling and boil for about two hours. A vigorous reaction takes place, resulting in the production of carbon dioxide and sulphur dioxide while the fuel slowly dissolves. Solution must be complete and the liquid a brownish yellow before the next step of oxidation.

Small portions of potassium permanganate are added with care, the oxidation being accompanied by detonations; the solution clears up and finally becomes a bluish-green. This is a signal that the oxidation is complete, and the contents are now digested at a gentle heat for ten minutes, then allowed to cool and poured into a 750-c.c. distilling flask, containing about 150 c.c. of water. The distilling flask is closed by a double-bore rubber stopper through which passes a separatory funnel and a glass tube, bent to form an inverted U. This glass tube is connected with a 50-c.c. pipette, which in turn enters a 250-c.c. Erlenmeyer flask, connected to a U-tube, both of which are immersed in a vessel of water. The U-tube and flask contain 30 c.c. of  $\frac{1}{2}$  normal sulphuric acid. Now 40 c.c. of 1.3 sp. gr. (30%) sodium or potassium hydroxide is run in from the separatory funnel, and gentle distillation is begun, con-

tinuing until one-half of the contents has passed over, or, say, 20 to 30 minutes. The addition of a few pieces of zinc will prevent bumping during distillation, but should nitrates be present (in the chemicals used) they will be reduced to ammonia and thus cause error. Any foaming or tendency of the liquid to spray over with the steam is to be carefully avoided.

The total distillate is collected in the flask and the excess acid titrated with alkali, standard solution, using litmus, methyl orange or phenacetolin (phenol phtalein) as an indicator. The ammonia equivalent, calculated, is reduced to nitrogen by the factor 0.82278.

*Note.*—The solution of the fuel in the acid is assisted by metallic oxides and some salts. The most active are cupric oxide and mercuric oxide. The latter must be prepared wet, as the dry preparation contains nitrogen compounds that will be reduced, in the distillation, by the zinc. The sulphates of these metals answer as well. Use about 0.75 gram. If these are used they must be precipitated, in the distillation flask, by an excess of 4% potassium sulphide solution. The proper amount can be found by testing 0.5 gram of the salt in solution. An excess must be used to decompose the mercurio-ammonium compounds. Even twice the amount actually required will usually do no harm, but more may result in a slight evolution of hydrogen sulphide.

*Determination of Oxygen.*—Oxygen cannot be directly determined with accuracy. If it were certain that the sulphur was present as pyrite, and that this is completely converted to ferric oxide in the ash, the oxygen would be, by difference, 100 minus the sum of carbon, hydrogen, nitrogen, ash and  $\frac{1}{4}$  of the sulphur. This is the best rule for the present, but the ash should be examined for sulphates and the rule modified where cause is found for its alteration.



**PART III**

---

**DESIGN OF FURNACES  
POWDERED FUEL**

**CHIMNEYS, REGÈNERATORS, RECUPER-  
ATORS, REVERSING VALVES, PORTS,  
HEARTHES, POWDERED FUEL**

**BY**

**A. L. J. QUENEAU**



## PART III.

### CHAPTER XV.

#### CHIMNEYS.

Chimneys are always necessary for evacuating the waste products into the atmosphere, no matter what the system of draught may be—natural or forced. In order to insure a draught in the chimney, the products of combustion must be delivered hot at the base of the stack. It will be shown that a temperature of  $200^{\circ}$  C. is amply sufficient. As the chimney operates through the difference of temperatures between the atmospheric air and the products of combustion, it follows that, the lower the temperature of the latter at the base of the stack, the better must be the construction of the stack, in view of keeping the heat radiation at a minimum. This is an important consideration if it is desired to operate the regenerative furnaces with the maximum fuel economy. Brick stacks are to be preferred for such purposes.

Calculation of the required height of chimney.—(The chimney height is taken from the level of the producer grate to the summit of the stack.)

Let  $L$  = the height of the chimney.

“  $t_1$  = the average temperature of the waste products in the chimney.

“  $\alpha$  = the dilatation coefficient of the air.

“  $t$  = the temperature of the atmospheric air.

“  $P_1$  = the weight of a column of waste products in the stack.

“  $P$  = the weight of a column of atmospheric air of a like volume.

“  $P_h$  = the pressure at top of the stack.

The difference in pressure at the grate is:

$$(Ph + P) - (Ph + P_1) = P - P_1 \quad (1)$$

This difference in pressure will produce the draught in the stack equal to a column of atmospheric air of height,  $h$ .

The gases issue from the stack at a velocity

$$V = \sqrt{2 g h} \quad (2)$$

$$(L + h)(1 + \alpha t) = L(1 + \alpha t_1)$$

$$h = \frac{L \alpha (t_1 - t)}{1 + \alpha t} \quad (3)$$

$\alpha t$  being a very small quantity, it will be sufficiently accurate to write

$$h = L \alpha (t_1 - t) \quad (3)^1$$

Substituting this value of  $h$  in (2),

$$V = \sqrt{2 g L \alpha (t_1 - t)}$$

Therefore:  $V$  varies as  $\sqrt{L (t_1 - t)}$

$V$  is proportional to the square root of the height of the chimney and to the difference in temperature. Let us find what temperature will give the maximum velocity.

Let  $\delta_0$  be the density of the air at the temperature  $t_1$  and pressure  $Ph + P_1$ .

The weight of air,  $Q$ , passing through a section  $S$ , per second, is

$$Q = SV\delta_1 = S\delta_1 \sqrt{2 g \alpha L (t_1 - t)}$$

Let  $\delta_0$  be the density of the air at  $0^\circ$  C. and pressure  $Ph + P_1$

$$\delta_0 = \frac{\delta_1}{1 + \alpha t_1} \quad Q = S \delta_0 \frac{\sqrt{2 g \alpha L (t_1 - t)}}{1 + \alpha t_1} \quad (4)$$



In order to find the maximum value of  $Q$ , it is sufficient to find the maximum of the expression  $\left( \sqrt{\frac{t_1 - t}{1 + \alpha t_1}} \right)$  since  $S \sqrt{2ga} L = K$  is a constant for a given height,  $L$ .

$$Q = K \sqrt{\frac{t_1 - t}{1 + \alpha t_1}}$$

Differentiating and equating to 0, we have

$$1 + \alpha t_1 = 2\alpha (t_1 - t)$$

$$t_1 = 2t + \frac{1}{\alpha}$$

$$\text{If } t = 0, \alpha = \frac{1}{273} \quad T_1 = 273^\circ \text{C.}$$

Let us find the values of the expression  $\sqrt{\frac{t_1 - t}{1 + \alpha t}} = \gamma$  for different temperatures for

$t_1 = 100^\circ$	$\gamma = 7.4$
200°	8.16
273°	8.255
300°	8.251
400°	8.110
500°	7.89

It follows that when the average temperature  $t_1$ , of the waste products, is  $100^\circ \text{C.}$ , the draught will be quite sufficient, and it will seldom be necessary to go beyond  $200^\circ \text{C.}$  This will give about  $300^\circ \text{C.}$  at the base of the stack.

From equation (4) it is seen that the quantity  $Q$  is directly proportional to the section  $S$ , and also to the square root of the height; it follows that it is more advantageous to increase the diameter than the height. A height of 30 to 40 meters is generally sufficient to insure a good draught.<sup>1</sup>

The nature of the surface is very important. Peclet has shown

<sup>1</sup> The case of deleterious fumes to be discharged into the atmosphere is not here taken into consideration.

experimentally that the velocity of gas in chimneys made of brick, plate iron and cast iron are as the numbers 2.00, 3.16, 4.47.

It is, then, possible to pass as much, per unit of time, through a cast-iron pipe one foot in diameter as in a brick flue two feet in diameter, the other factors being equal.

The friction increases with the perimeter of the conduct. As, however, the section increases, the ratio  $\frac{\text{perimeter}}{\text{section}}$  decreases rapidly, the two factors increasing and the friction becomes less important after a certain ratio has been reached. The ratio  $\frac{\text{perimeter}}{\text{section}}$  must be as small as possible; the circular section is, therefore, the best, and other sections will become less efficient the farther they are removed from the circle.

Elbows and contractions increasing greatly the friction, they should be avoided as far as possible. All bends should have generous diameters.

Section of Stack.—Redtenbacher's formula gives

$$S = \frac{K}{42L} = \frac{h}{84\sqrt{L}}$$

S is the section in square meters.

K is the kilograms of coal burned per hour.

L is the height in meters.

He also gives the following formulas:

$$\text{Height of chimney} = \frac{L^2}{10^3 q^2}$$

$$\text{Cross-section in sq. m.} = \frac{L}{10^3 \sqrt{h}}$$

When L = Weight of waste products per kg. per hour.

q = Cross-section of stack in sq. m.

h = Height of stack in meters.

For the velocity of the gas leaving the chimney, we have Peclet's formula,

$$v = \phi \frac{\sqrt{2gh(T-t)}}{273+t}$$

T and t are temperatures.

h is the height of the stack.

g is the acceleration of gravity, 9.81.

$\phi$  is a coefficient varying between .38 and .85.

Giesker gives for it a value of .33.

Redtenbacher also states that the height of the chimney should not be less than 16 meters and equal to 25 times its smallest diameter.

Pinzger gives 2 meters per second as the allowable minimum velocity in the stack. Gruner states that, for temperatures between 200° and 300° C., the velocity may reach 5 meters per second; for higher temperatures it may reach 10 meters per second. The reduction of temperature in an underground flue has been found by Jüptner and Toldt to be, in one instance, 1.46° C. per running meter, and they consider that, for chimney calculations, it is safe to assume a cooling of about 3° C. per running meter of chimney height.

It is, in general, preferable to give to each furnace its own stack, as the regulation of the draught is then made easier and more effective. The draught is better regulated by means of a damper placed on the top of the stack than by a register in the flue leading to the base.

*Example.*—A furnace burns in three gas-producers 11,077 kg. of anthracite coal per 24 hours. In allowing for the carbon content of the ash, the composition of the anthracite is as follows:

Carbon burned.....	52.9%
Carbon lost in the ash.....	5.5
Ash.....	30.2
H <sub>2</sub> O.....	4.85
S.....	.67
H <sub>2</sub> , N <sub>2</sub> , O <sub>2</sub> .....	5.88
Total.....	100.00

The gas has the following analysis:

	% by volume	% by weight	Carbon contents in grs. per 100 liters of dry gas
CO <sub>2</sub> .....	10.21	18.09	4.930
CO.....	20.31	22.92	9.837
H <sub>2</sub> .....	18.71	1.51	.....
N <sub>2</sub> .....	50.77	57.47	.....
H <sub>2</sub> O.....	5.50	3.99	.....
Total.....	.....	.....	14.767

The carbon coming wholly from the coal, it is possible to find the volume of gas produced per minute.

105.50 liters of wet gas at 0° C. and 760 mm. pressure carry 14.767 grams of carbon.

128 grams. of coal per second =  $128 \times .529 = 67.82$  grams of carbon. Number of cubic meters of wet producer-gas obtained from

$$67.82 \text{ grams carbon} = \frac{67.82 \times .10550}{14.767} = .4845 \text{ cu.m. at } 0^\circ \text{ C.}$$

and 760 mm. At 300° C. we have  $.4845 \times 2.1010 = 1.018$  cu. m.

Composition of the waste products:

	% by volume	% by weight	Carbon contents in grs. per 100 liters of dry gas
CO <sub>2</sub> .....	14.51	20.86	5.684
O <sub>2</sub> .....	4.85	5.07	.....
N <sub>2</sub> .....	80.64	74.04	.....
H <sub>2</sub> O.....	6.10	3.59	.....

Volume of the waste products per second, at 0° C. and 760 mm. pressure,

$$\frac{67.82 \times .1061}{5.684} = 1.266 \text{ cu.m.}$$

Weight of the waste products per second = 1.691 kg.

L = Weight of the waste products per hour =  $3600 \times 1.691 = 6087$  kg.

According to Redtenbacher,

$$q = \frac{L}{10^3 \sqrt{h}}$$

Making  $h = 36$  m.

$$q = \frac{6087}{10^3 \sqrt{36}} = \frac{6087}{6000} = 1.015 \text{ sq. m.}$$

The stack is to be built with a circular section; therefore the mean diameter,

$$D = 1.136 \text{ m.}$$

With a batter of 13 mm. per running meter, the top diameter will be

$$1.136 - (18 \times .013) = .902 \text{ m.}$$

and the base diameter,

$$1.136 + (18 \times .013) = 1.370 \text{ m.}$$

In Prechtl's table, the stack, for a fuel consumption of 460 kg. per hour, should have a diameter of 2.0 m. at the base and 1.33 m. at the top. (See table 23.)



## CHAPTER XVI.

### REGENERATORS.

In the general theory, no distinction was made between the two systems of recuperation, the Siemens and the parallel counter-current. Now that we have reached the design of furnaces, it is necessary to make distinction between them; each has its own field, its advantages and drawbacks.

In the Siemens system the chambers are partly filled with a checkerwork of firebricks. The bricks are heated by passing the products of combustion through the chambers during one period. By reversing the valve the flow of waste products is stopped, and in their place either gas or air enters to be pre-heated. The heat stored in the bricks during the passage of the hot products of combustion is now restored to the incoming cold gases until the end of this period, when the valves are again reversed and the waste products admitted anew.

It follows that at each reversal there will be a sudden rise of temperature, and also that, by having shorter periods between the reversals, it will be possible to increase rapidly, within limits, the temperature of the pre-heated gases and thereby their temperature of combustion; this will result in an increased temperature in the hearth.

In the parallel counter-current system the air alone is pre-heated. The recuperator is composed of a series of tubes through which the secondary air circulates, the tubes being entirely surrounded by the waste products traveling in a reverse direction. In this case the calories stored by the outer surfaces of the tubes are conducted through the thickness of the walls and are restored by the inner surfaces by radiation and convection. The gaseous currents flowing always in the same direction, valves are dispensed with. Once the equilibrium has been reached in the furnace the air will be pre-heated to practically a uniform temperature.

From the manner in which the calories are accumulated and restored in the two systems, it follows that the Siemens will be the more efficient. In practice the difference of temperature between the waste products leaving the hearth and the gases entering is about 300° C. in the first system, while in the second system the difference is over 600° C.

It is impossible to increase the temperature of the hearth rapidly in the second system, while this is easily done in the first. The gas cannot be pre-heated in the parallel counter-current system on account of the soot deposition, which would choke the tubes; this, however, is true only of the gas made from bituminous coal, as with anthracite gas, practically free of hydrocarbons, there is little soot deposition.

In case of low temperatures, the tubes can be made of cast iron; metals must be discarded if the temperature of the pre-heated gas reaches above 500° C. Beyond that point it becomes necessary to make use of perforated firebricks. The efficiency drops very much in passing from one material to the other, on account of the low coefficient of conductivity of firebricks.

With the use of bricks it is very difficult to keep the passages air-tight. The hollow potteries can be made only in short lengths, and numerous joints are necessary. When the furnace is started it is seen, by the examination of the furnaces illustrated in Figs. 33, 35 that the heating of the recuperators begins endways; there is, then, an unequal expansion which causes some of the joints to tear loose, and they remain so to the end of the campaign. A. Lodin<sup>1</sup> gives an example of a recuperative illuminating gas furnace. Samples of the products of combustion were taken at the points of entrance and exit of the recuperator. The average of twelve analyses is as follows:

	Entrance	Exit
CO <sub>2</sub> .....	17.04	10.34
CO.....	1.20	none
O <sub>2</sub> .....	1.67	9.05
N <sub>2</sub> .....	80.09	80.61

<sup>1</sup> A. Lodin, "Metallurgie du Zinc," Paris. 1905.

In a parallel current recuperative zinc furnace that came under the observation of the writer, the average of five analyses taken at the points of entrance and exits of the products of combustion gave the following:

	Entrance	Exit
CO <sub>2</sub> .....	16.72	13.96
O <sub>2</sub> .....	2.72	6.33
N <sub>2</sub> .....	80.56	79.71

The large admixture of atmospheric air to the products of combustion on their way to the stack tends to lower their temperature, and if care is not taken to detect the error, the furnace will appear to have a very good fuel efficiency when in actuality it has not.

There remains the very great advantage of operating without valves.

The parallel counter-current system from its nature is well suited to furnaces fired at medium temperatures, as zinc-reduction furnaces, brass-melting furnaces, illuminating-gas muffle furnaces, billet reheating furnaces, etc.—all furnaces requiring a uniform temperature or a progressive rise of temperature distributed over a number of hours. This uniformity of temperature of the hearth may result in economies which will easily offset the low-fuel efficiency.

In muffle furnaces, in which the vessels are made of fireclay, the varying temperatures of the Siemens furnace may cause a higher loss of vessels than in a parallel counter-current furnace, and the increased expenditure of costly muffles will offset the saving in fuel due to better heat recuperation.

*Maximum Allowable Velocities of Gas Currents in the Various Parts of Regenerative Furnaces.*<sup>1</sup>

	M. per Sec.
Velocities of the air and gas through the reversing valves....	3.5
Velocity of the gas entering the regenerator.....	3.0
Mean velocity of the gas through the regenerator (not over)	1.0
Mean velocity of the gas through the brick checkerwork (not over).....	2.0

<sup>1</sup> From F. Toldt, *loc. cit.* p. 262.



Velocity of the gas in the free space over the checkerwork...	0.5
Velocity of the gas issuing through the ports .....	8.0
Velocity of the air in the flue leading to the regenerator.....	3.0
Mean velocity of the air through the regenerator (not over)...	2.0
Velocity of the air in the free space over the checkerwork..	0.5
Mean velocity of the air through the regenerator (under)...	1.0
Velocity of the air issuing from the ports.....	8.0
Velocity of the products of combustion through the hearth..	2.0

*Minimum Times of Sojourn of the Gaseous Currents in the Various Parts of Regenerative Furnaces.*

	No. of Sec.
Gas in the regenerator.....	4
Gas in the checkerwork.....	3
Air in the regenerator .....	5
Air in the checkerwork .....	3
Products of combustion in the hearth.....	2

The figures given were considered proper for the following temperatures:<sup>1</sup>

Temperature of the producer-gas in the flue leading from the reversing valve to the regenerator.....	400° C.
Temperature of the air at the reversing valve .....	30° C.
Temperature of the air in the flue leading from the reversing valve to the recuperator.....	270° C.
Temperature of the gas leaving the regenerator .....	850° C.
Mean temperature of the gas in the regenerator.....	625° C.
Temperature of the air leaving the regenerator.....	950° C.
Mean temperature of the air in the regenerator.....	610° C.
Temperature of the products of combustion in the hearth.	1600° C.
Temperature of the products of combustion entering the regenerator.....	1600° C.
Temperature of the products of combustion after passing through the reversing apparatus.....	300° C.

The velocities and the times of sojourn will vary according to the temperature.

<sup>1</sup> From Le Chatelier, "Comptes Rendus," Vol. CXIV, 1892, p. 470.

It is well known that the design of furnaces cannot generally be made to follow the dimensions given by mathematical calculations. The available room, as well as economy, will often necessitate curtailments of the dimensions as well as change in the grouping of the various organs. In all cases, however, it is well and necessary to know what should be had in order to make the best use of what is at hand. Paul Héroult said that success followed him only as far as his tests had been based on previous theoretical analysis and calculations.

### REGENERATORS.

As a general rule, regenerative chambers have too small volumes. Nevertheless, it is well to remember that regenerators may be made too large. Discounting the valuable space that they would occupy, and their increased first cost, they present also thermic disadvantages. The radiation becomes very high, and we have seen that this item is far from being negligible. It amounts in most cases to 18% or more of the total available calories. As the volume of the gas chambers is increased, the loss due to the gas filling it at the time of reversal is also increased. Finally the temperature of the waste products may be rendered so low as to impair the chimney efficiency. We have seen that the temperature of the waste products should not be lowered much below 200° C. (see page 233).

The chambers, as far as possible, should be grouped in one block approaching the cubic form in order to reduce the loss due to radiation. Chambers of cylindrical shape offer the minimum perimeter; if they are isolated, as in the Batho furnace, the radiation losses are higher than in grouped cubical chambers. For the same reasons, the walls should not be made less than 440 mm. in thickness, and better 550 mm; the dividing walls need, also, to be of the same thickness, in order to reduce the leakage through them. The chambers may be constructed with the longer axis either vertical or horizontal. It may be stated, in a general way, that vertical chambers have a better thermic efficiency.

It is of the greatest importance that the flue extending under the checkerwork have a sufficiently ample cross-section, so that

the gaseous currents will be forced to distribute themselves throughout the whole mass of the checkerwork.

Moving masses do not change their paths of motion unless compelled to do so. This elementary law of mechanics is very often disregarded, not only in regenerators and recuperators, but also in many engineering applications. It is a common occurrence to see a flue leading to a number of subsidiary pipes, through which a gas current is to be divided, of such diameter that practically the pipes furthest removed will receive all the gas.

In a certain recuperative muffle furnace, the distributing air flue had a cross-section smaller than the total section of the subsidiary

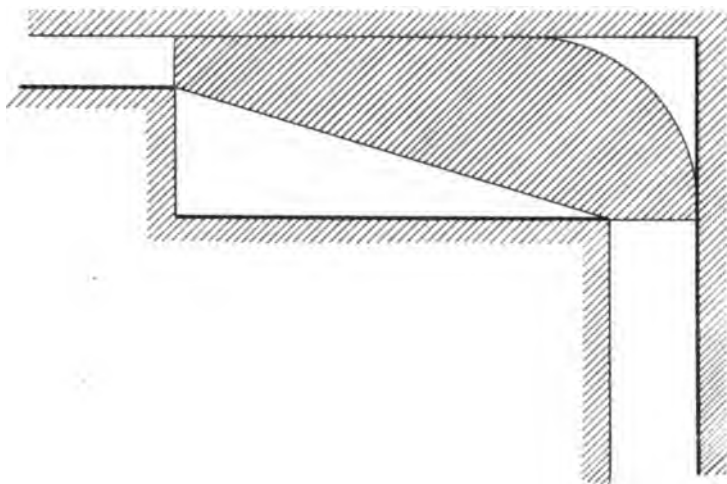


FIG. 75.—INCORRECT FLUE CONNECTIONS FOR A HORIZONTAL REGENERATIVE CHAMBER.

The hatched area represents the path of the gas currents.

From F. Toldt, "Regenerativ Gasöfen."

pipes; the result was that only a few of these received any air. The heat recuperation became practically nil, and barely 25% of the total available heat was utilized in the hearth.

In the Schoenwalders furnace, this principle is very carefully emphasized; the lower flue is made very large and the chamber is

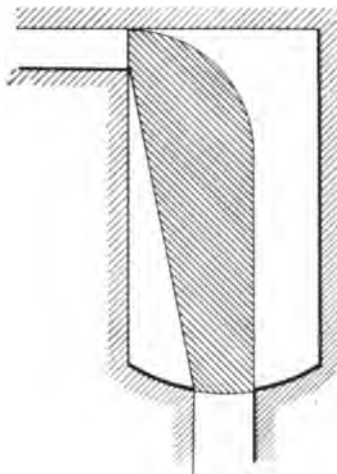


FIG. 76.—INCORRECT FLUE CONNECTIONS FOR A VERTICAL REGENERATIVE CHAMBER.

The hatched area represents the path of the gas currents.

From F. Toldt, "Regenerativ Gasöfen."

subdivided by a wall reaching to the upper level of the checkerwork, each chamber having its own flue connecting with the reversing valve.

The upper flue, collecting the heated gases (air or producer-gas),

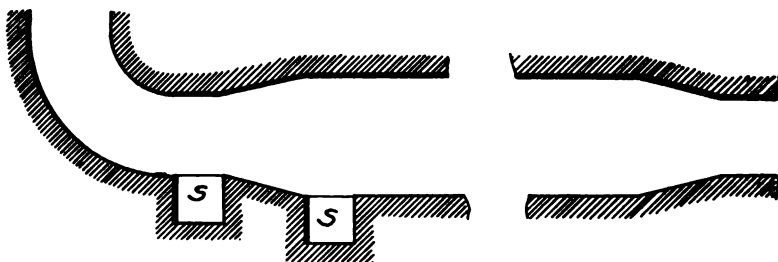


FIG. 77.—CORRECT FLUE DESIGN FOR A HORIZONTAL REGENERATIVE CHAMBER.  
S S, SLAG AND DUST CATCHER.

From F. Toldt's "Regenerativ Gasöfen."

should also be of generous cross-section, in order that, on the waste-product phase, they may distribute themselves uniformly throughout the entire volume of the checkerwork.

The design of flues leading to the chambers requires careful attention and consideration in order to utilize the whole of the checkerwork. (Fig. 75, 76, 77.)

In Fig. 32, the chambers are built according to these considerations; it may be further mentioned that the chambers are very happily grouped with respect to the radiation losses.

In the case of muffle furnaces, the chambers are conveniently and properly placed below the hearth. On the contrary, the hearths of steel furnaces or glass tank furnaces have no connection with the chambers, as the support given to the hearth would be very precarious, subjected, as it would be, to the sudden changes due to the heating and cooling of the chambers.

The chambers should be provided with ample dust- and slag-settlers; they will protect, in large measure, the checkerwork from the accretions, which rapidly reduce the open spaces and soon necessitate laying the furnace up for repairs.

In zinc metallurgy peculiar conditions obtain which necessitate the air- and gas-chambers being made of equal volumes. On account of the leakage of the zinc vapor through the walls of the muffles, as well as through the cracks of broken muffles, the waste products carry an appreciable amount of zinc oxide. This settles on the checkerwork and in time closes the free passages. If, however, the gas is turned into the air-chambers, there is a reaction between the zinc oxide and the carbon of the soot brought in by the gas, a metallic zinc being formed. This is carried away by the waste products, thus cleaning the chambers.

The ratio of the width of the open channels to that of the dividing walls should be in relation to the specific heats of the gases and of the firebricks. The open spaces should be larger in the gas-chambers than in the air-chambers, in which the ratio may be made equal to unity. In most instances, however, the ratio of the volume of the checkerwork to the free space is much below unity, and this point cannot be directly taken into consideration.

There is a great diversity of opinion among authorities in regard

to the proper dimensions for regenerators. Breslauer<sup>1</sup> gives the following figures as ratio between the volume of a set of chambers in cubic meters and the steel production in metric tons per hour.

Dowials.....	14.60	Terre Noire.....	30.00
Gras.....	15.50	Krupp (3-ton furnace).....	36.00
Haleside.....	16.75	Swedish furnace.....	36.60
Krupp (large furnace).....	18.32	Borsigwerk.....	44.00
Landore.....	20.00		
Pateg.....	20.60	Steelton (50-ton furnace) <sup>2</sup> .....	37.45

Siemens recommends a total surface of 51 sq. m. of checkerwork per 1000 kg. of coal consumed in 24 hours, or 25.15 sq. m. per chamber.

In regard to the weight to be given to the chamberwork, Grüner states that for each kilogram of coal consumed between two reversals 50, and better 60, kilograms of checkerwork should be allowed for one set of regenerative chambers. Toldt goes a step further, and gives the following rule for the determination of the volume and weight to be given to the checkerwork:

"A volume of 6 cu. m. and a weight of 2850 kg. should be provided per cubic meter of gas or air (at 0° C. and 760 mm. pressure) for each 100° C. rise in the temperature in the regenerator."

This rule, in terms of Grüner, would give 71 kg. per kg. of coal consumed between two reversals.

H. H. Campbell<sup>3</sup> states that the combined volume of checkerwork per set of chambers should be, as a minimum, 50 cu. ft. per ton of steel in the furnace, and double that amount to obtain the best results. In a 40-ton furnace of the Pennsylvania Steel Company, at Steelton, Pa., the volume is 65 to 70 cu. ft. In a 50-ton furnace, the illustration of which is given in Fig. 39, the volume is 100 cu. ft.; in a 30-ton furnace at Donawitz, Austria, the volume is 110 cu. ft., while it is 50 cu. ft. in a furnace at Sharon, Pa.; also 50 cu. ft. for a 50-ton furnace at Duquesne, Pa., burning natural gas and having only two chambers, the air-chambers, affording nearly the capacity recommended.

<sup>1</sup> Breslauer, "Der Stahlguss in Masseformerei."

<sup>2</sup> Computed from data given, H. H. Campbell, *loc. cit.*

<sup>3</sup> H. H. Campbell, *loc. cit.*, page 190.

In cubic meters and metric tons, we have the ratio

$$\frac{142}{45.4} = 3.12 \text{ or } 3.12 \text{ cubic meters}$$

of the combined capacity of one set of chambers per metric ton of furnace capacity. In terms of Breslauer, the 50-ton Steelton furnace has a ratio of about 37.45. It is more direct and simpler than any of the rules giving the volume of the checkerwork as a function of the weight of coal burned, or of the volume of gas burned per unit of time. In a 40-ton Bain furnace, given by F. W. Harboard<sup>2</sup>, the ratio is 1.24.

Comparison of H. H. Campbell<sup>3</sup> with Toldt's rules: The figures given are from the thermic analysis of the work of a 50-ton furnace (Fig. 39). Assuming that a 50-ton charge is worked in twelve hours—

Coal consumed per charge,  $50 \times 200 = 10,000$  kg.

Total carbon in the coal, 75.60%.

$$\text{Coal consumed per second} = \frac{10,000}{12 \times 3600} = .231 \text{ kg.}$$

If deduction is made for the carbon in the ash, the carbon contents are 73.78%. The total carbon burned per second is then  $.231 \times .7378 = .1704$  kg.

Analysis of producer-gas		Carbon contents in grams per 100 liters of dry gas
CO <sub>2</sub> .....	5.7%	3.06
CO.....	22.0	10.80
CH <sub>4</sub> .....	2.6	1.40
C <sub>2</sub> H <sub>4</sub> .....	0.6	0.64
H <sub>2</sub> .....	10.5	.....
O <sub>2</sub> .....	0.4	.....
N <sub>2</sub> .....	58.2	.....
Total.....	.....	16.00

<sup>2</sup> F. W. Harboard, "Steel," page 145.

<sup>3</sup> J. W. Richards in H. H. Campbell, *loc. cit.*, page 128.

The gas carried .0375 cubic meter of steam per cubic meter of dry gas. Cubic meters of dry gas produced per second,

$$\frac{.1704}{.160} = 1.065.$$

Cubic meters of wet gas produced per second,

$$1.065 \times 1.0375 = 1.105.$$

If we assume the same rise of temperature as Toldt, the volume of the gas chambers will be

$$1.105 \times 6.0 \times 4.5 = 29.84 \text{ cu. m. or}$$

$$29.84 \times 35.3145 = 1053 \text{ cu. ft.}$$

The 50-ton Steelton furnace has about 3315 cu. ft. of checkerwork for one gas-chamber. Thus the required capacity, according to Toldt, is about one-third of that of the standard American practice.

In terms of the weight of coal burned per minute, the Grüner rule should be amended as follows:

*The weight of the checkerwork should be of 230 kg. per kilogram of coal burned between two reversals.*

The air-chambers should have a larger volume than the gas-chambers. A ratio of 1 : 1.37 is proposed by H. C. McMillan.<sup>1</sup> He recommends in the same paper 15 ft. as the minimum depth of chambers, and preferably 20 ft. Ledebur favors a ratio of the volume of air to gas of 4 : 3 or 3 : 2.

*Calculation of the checkerwork necessary for a furnace consuming 17,000 kg. in 24 hours.* The ash, weighing 4000 kg., has the following composition:

Water.....	28%
Carbon.....	40
Ash.....	32

The elementary analysis of the coal is as follows:

Carbon.....	82.5	} 100.00
Hydrogen.....	5.0	
Nitrogen.....	1.2	
Oxygen.....	6.0	
Ash.....	4.1	
Moisture.....	1.2	
Calorific power 8210 cal.		

<sup>1</sup> H. C. McMillan, *Proceedings Institute of Cleveland Engineers*, Jan. 1903.



Carbon in the coal,  $17,000 \times .825 = 14,030$  kg.

Carbon in the ash,  $4,000 \times .40 = 1600$  kg.

The carbon lost amounts to 11.41% of the total carbon of the coal.

Recasting the elementary analysis, we have,

Carbon utilized.....	73.1%	} 100.0
Carbon lost in ash.....	9.4	
Hydrogen.....	5.0	
Nitrogen.....	1.2	
Oxygen.....	6.0	
Ash.....	4.1	
Moisture.....	1.2	

The gas has the following composition:

Gas	By Volume	By Weight	Grams of C per 100 liters of dry gas
CO <sub>2</sub> .....	5.2	9.12	2.79
CO.....	20.3	22.65	10.90
H <sub>2</sub> .....	13.2	1.05	.....
CH <sub>4</sub> .....	3.1	1.98	1.66
N <sub>2</sub> .....	58.2	65.20	.....
H <sub>2</sub> O.....	2.5	1.79	.....
Total.....	.....	.....	15.35 Gr.

Weight of coal consumed per second,  $\frac{17,000}{86,400} = .197$  kg.

This coal contains  $.197 \times .731 = .144$  kg. of carbon.

Cubic meters of producer-gas per second,

$$\frac{.144}{.1535} = .937 \text{ cu. m. of dry gas, or}$$

$.937 \times 1.025 = .960$  cu. m. of wet gas at 0° C. and 760 mm. pressure.

The products of combustion have the following volumetric analysis:

CO <sub>2</sub> .....	14.3	} 100%
N <sub>2</sub> .....	84.0	
O <sub>2</sub> .....	1.7	
H <sub>2</sub> O.....	8.7	

The air required for combustion, per unit volume of gas, taking into account the excess of oxygen in the waste products (see table13):

	20.3 vol. CO	require	10.15 vol. O <sub>2</sub>	+	38.85 vol. N <sub>2</sub>
	13.2 " H <sub>2</sub>	"	6.60 " O <sub>2</sub>	+	25.13 " N <sub>2</sub>
	3.1 " CH <sub>4</sub>	"	6.20 " O <sub>2</sub>	+	23.61 " N <sub>2</sub>
Excess	$\frac{28.6}{14.3} \times 1.7$	O <sub>2</sub>	3.40 " O <sub>2</sub>	+	12.94 " N <sub>2</sub>
		Total,	26.35		100.53

Total volume of air, 126.88

or 100 volumes of gas require 126.88 volumes of air, one volume requires 1.2688.

Volume of air in cubic meters per second:

$$.960 \times 1.2688 = 1.218 \text{ cu. m., at } 0^\circ \text{ C. and 760 mm. pressure.}$$

*Minimum Section of the Gas- and Air-Flues Leading to the Regenerator.*

Temperature of the gas, 400° C.

Temperature of the air, 270° C.

Volume of the gas at 400° C.:

$$.960 (1 + \alpha t) = 2.468 \times .960 = 2.370 \text{ cu.m.}$$

Maximum allowable speed, 3.0 meters per second.

$$\text{Minimum section } \frac{2.370}{3.0} = .79 \text{ sq. m.}$$

Volume of the air at 270° C.:

$$1.218 (1 + \alpha t) = 1.218 \times 1.9909 = 2.425 \text{ cu. m.}$$

$$\text{Minimum section } \frac{2.425}{3.0} = .808 \text{ sq. m.}$$

From the temperature given on page 241, the gas has a temperature of 850° C., as it comes from the regenerator, and 400° as it enters the checkerwork. The rise of temperature is, therefore, 450° C.

According to Toldt's rule, the cubic contents and weight of the checkerwork for the gas regenerator is found as follows:

Cubic contents  $.960 \times 6 \times 4.5 = 25.92$  cu. m.

Weight of checkerwork  $2.850 \times 4.5 \times .960 = 12,312$  kg.

Volume occupied by the checkerwork,

$$\frac{12,312}{1800} = 6.87 \text{ cu. m.}$$

Volume left vacant, 19.08 cu. m.

Volume of the gas at  $625^{\circ}\text{C.}$ ,  $.960 \times 3.2938 = 3.162$  cu. m.

Time of sojourn  $\frac{19.08}{3,162} = 6.03$  seconds.

*Air Regenerator.*

Volume of air = 1.218 cu. m. per second, at  $0^{\circ}\text{C.}$  and 760 mm. pressure.

The air enters at  $270^{\circ}\text{C.}$  and leaves at  $950^{\circ}\text{C.}$ , a rise of  $680^{\circ}\text{C.}$

Volume of the checkerwork =  $1.218 \times 6.80 \times 6 = 49.46$  cu. m.

Weight of the checkerwork =  $1.218 \times 2850 \times 6.8 = 23,500$  kg.

Taking the weight of firebrick at 1800 kg. per cu. m., the volume occupied by the brick is

$$\frac{23,500}{1800} = 13.05 \text{ cu. m.}$$

leaving 46.41 cu. m. for the air.

Volume of the air at  $680^{\circ}\text{C.}$ :

$$1.218 (1 + \alpha t) = 1.218 \times 3.2387 = 3.945 \text{ cu. m.}$$

The air would remain

$$\frac{36.41}{3.945} = 9.23 \text{ seconds.}$$

*Cross Section of the Ports.*

Allowable velocity of the air and gas, 8 m. per second.

Temperature of the air,  $950^{\circ}$ .

Temperature of the gas,  $850^{\circ}$ .

Volume of the air at  $950^{\circ}$ ,  $1.218 \times 4.4865 = 5.465$  cu. m.

Volume of the gas at  $850^{\circ}$ ,  $.960 \times 4.1195 = 3.954$  cu. m.

Cross-section of the air-port,  $\frac{5.465}{8} = .683$  sq. m.

Cross-section of the gas-port,  $\frac{3.954}{8} = .494$  sq. m.

## CHAPTER XVII.

### RECUPERATORS.

*Calculation of the Dimensions to be Given to the Recuperative Surfaces for a Muffle Furnace.*—The data given in the design of a chimney will again be made use of in connection with the recuperator.

Volume of gas generated per second at 0° C. and 760 mm. pressure = .4845 cu. m.

#### *Volume of Air Injected Per Unit Volume of Gas.*

20.31 vol. of CO require 10.155 vol. of O<sub>2</sub> + 38.67 vol. of N<sub>2</sub>,  
(See table 14.)

18.71 vol. of H<sub>2</sub> require 9.355 vol. of O<sub>2</sub> + 35.62 vol. of N<sub>2</sub>,  
Excess of O<sub>2</sub>, ..... 10.53 vol. of O<sub>2</sub> + 40.10 vol. of N<sub>2</sub>,

(See page 236.) Totals 30.040 vol. O<sub>2</sub>      114.39 vol. N<sub>2</sub>

Total volume of air = 144.43 vol.

or 100 volumes of gas require 144.43 volumes of air. One volume of gas requires 1.4443 volumes of air.

Volume of air injected per second:

$$.4845 \times 1.4443 = .700 \text{ cu. m.}$$

At 0° C. and 760 mm. pressure.

Weighing  $.700 \times 1.293909 = .906$  kg.

Volume of the wet waste products, <sup>1</sup> 1.343 cu. m.

The waste products enter the recuperator at a temperature of 1340° C. We will assume that the temperature has fallen to 400° C. at the recuperator exit; their average temperature is then 870° C.

The total heat capacities of the products of combustion at 1340° C. and 400° C. are found as follows:

<sup>1</sup> The volume of the products of combustion has been assumed to be 1.343 c.m. instead of 1.266 used in the stack calculations.

They contain per weight

.361 kg. of CO<sub>2</sub>,  
 .088 kg. of O<sub>2</sub>,  
 1.282 kg. of N<sub>2</sub>,  
 .066 kg. of H<sub>2</sub>O

From Fig. 88 the heat capacities at 1340° C. are:

Gas	Weights	Heat Capacities in Calories	Calories
CO <sub>2</sub> .....	.361	411.0	148.5
O <sub>2</sub> .....	.088	318.0	28.0
N <sub>2</sub> .....	1.282	366.0	469.0
H <sub>2</sub> O.....	.066	897.0	59.1
Total.....			704.6

At 400° C. we have:

Gas	Weight	Heat Capacities	Calories
CO <sub>2</sub> .....	.361	× 91.	= 32.9
O <sub>2</sub> .....	.088	× 88.	= 7.7
N <sub>2</sub> .....	1.282	× 100.	= 128.2
H <sub>2</sub> O.....	.066	× 205.	= 13.5
Total.....			= 182.3

Then the available number of calories per second is

$$704.6 - 182.3 = 522.3$$

The air enters the flue leading to the recuperator at 30° C. and leaves the recuperator at 930° C., a rise of 900°.

The volume of air to be pre-heated is .700 cu. m., weighing .960 kg. It contains .698 kg. of nitrogen and .208 kg. of oxygen.

Heat capacities of the injected air at 930° C.:

Gas	Weight	Heat Capacities	Calories
O <sub>2</sub> .....	.208	207.	43.4
N <sub>2</sub> .....	.698	234.	163.3
Total.....			206.7

Heat capacities of the air at 30° C.:

Gas	Weight	Heat Capacities	Calories
O <sub>2</sub> .....	.208	6.55	1.36
N <sub>2</sub> .....	.698	7.50	5.25
Total.....	.....	.....	6.61

Calories to be taken from the waste products between 30° C. and 930° C.,

$$206.7 - 6.6 = 200.1 \text{ calories.}$$

Thus  $\frac{200.1}{522.3} = 38.3\%$  of the total available calories contained in the products of combustion are utilized, leaving a large margin for losses through radiation, etc.

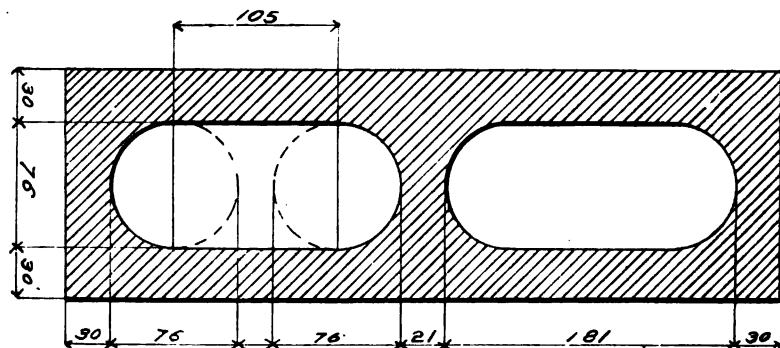


FIG. 78.—SECTION OF PERFORATED BLOCK.

The perforated blocks are shown in Fig. 80. In order to simplify the calculations, all the formulas being in terms of cylindrical tubes, we will make use of a perforated block of circular section, equivalent in area to one of the perforations of the fire-brick block.

Area of the cross-section of one perforation,

$$\frac{.076^2 \pi}{4} + (.076 \times .105) = .01251 \text{ sq. m.}$$

The diameter of the equivalent circle,

$$d = .126 \text{ m.}$$

The diameter of the outer cylinder,

$$D = .126 + (2 \times .030) = .186 \text{ m.}$$

Area of the inner surface of block, one meter long,

$$\pi D l = .397 \text{ sq. m.}$$

Volume of the enclosed air-column,

$$\frac{\pi D^2 l}{4} = .01251.$$

Weight of the air-column,

$$.01251 \times 1.2939 = .0162 \text{ kg.}$$

The total number of calories to be absorbed by the air per hour

$$200.1 \times 3600 = 720,360 \text{ calories.}$$

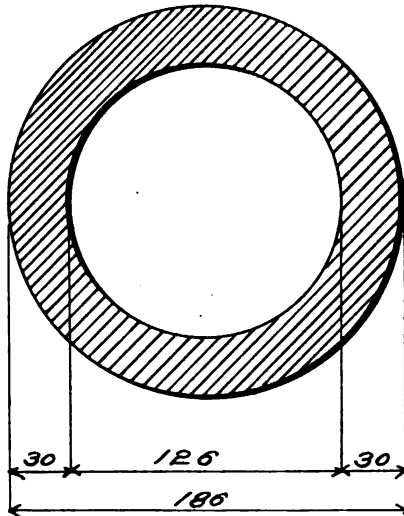


FIG. 79.—SECTION THROUGH CYLINDRICAL TUBE, EQUIVALENT TO ONE HALF OF THE PERFORATED BLOCK.

Let us find the number of calories,  $W$ , that can be transmitted per hour through the equivalent cylindrical tube, one meter long,

$$W = CF \tau \quad (1)$$

In which  $C$  = Coefficient of heat transmission.

$F$  = Inside surface of cylinder.

$$\tau = t_1 - t_2.$$

$t_1$  = Mean outside temperature  $870^\circ \text{C}$ .

$t_2$  = Mean inside temperature  $480^\circ \text{C}$ .

$$\tau = 870^\circ - 480^\circ = 390^\circ.$$

The formula giving the value of the coefficient  $C$  is as follows:

$$\frac{1}{C} = \frac{1}{a_1} \frac{D}{D} + \frac{1}{a_2} + \frac{D}{2\lambda} \log. \text{ nep. } \frac{D}{d} \quad (2)$$

In which  $a_1$  and  $a_2$  are the coefficients of heat transmission for the outer and the inner surfaces.

$D$  = outer diameter.

$d$  = inner diameter.

$\lambda$  = coefficient of heat conductivity of bricks = .7.

$a_1$  for both surfaces = 8.

$a_2$  is given by the formula,

$$a_2 = 125 S \frac{1.0077^{t_1} - 1.0077^{t_2}}{t_1 - t_2} + .55 b (t_1 - t_2)^{.333} \quad (3)$$

Where  $S'$  = radiation coefficient of firebrick = 3.60.

$b$  = convection coefficient of air.

Valerius gives for confined air,  $b = 4$ .

For air in a free space,  $b = 5$  to 6.

The air being in motion, the higher coefficient will be taken, or, substituting in (3),

$$b = 6$$

$$a_2 = 125 \times 3.6 \frac{1.0077^{870} - 1.0077^{480}}{390} + .55 \times 6 \times 390^{.333}$$

$$a_2 = 454.5 + 13.25 = 467.75.$$

<sup>1</sup>A very interesting paper has recently appeared on the quantitative radiation of flues and furnace surfaces, by J. Biedl, in *Revue de Metallurgie*, Sept., 1905.



Substituting in (2),

$$\frac{1}{C} = \frac{1}{8} \times \frac{.126}{.186} + \frac{1}{467.75} + \frac{.126}{1.4} \log. \text{ nep. } \frac{.186}{.126}$$

$$\frac{1}{C} = .1218.$$

$$C = 8.21.$$

Substituting in (1),

$$W = 8.21 \times .397 \times 390 = 1271 \text{ calories per hour.}$$

Length of tubes required to transmit the necessary number of calories,

$$\frac{720,360}{1271} = 567 \text{ meters.}$$

As each block has two perforations, the length of blocks required is

$$\frac{567}{2} = 283.5 \text{ m.}$$

The blocks are made conveniently in 292 mm. lengths. The bricks used as spreaders between the perforated blocks are  $66 \times 182$  mm., taking 33 mm. from the length of each block; thus reducing their effective length to 259 mm.

Total length of blocks,

$$\frac{292 \times 283.5}{259} = 320 \text{ m.}$$

For the general design of ports, see Fig. 31 and 32, while for the recuperator, see Fig. 33 and 35.

The blocks are placed side by side (Fig. 80), and only about one-half of their inner surfaces are placed at the distance of 30 mm. from the outer surfaces, as was assumed in the calculations; the total length found should be correspondingly increased.

$$\text{Revised total length, } \frac{320 \times 3}{2} = 480 \text{ meters.}$$

For practical considerations the over-all width of the recuperator cannot exceed 5.18 m. To insure the proper air distribution

throughout the entire section of the recuperator it will be divided into two chambers. The secondary air will be offered a free vertical path from the lower distributing flue to the upper collecting flue. The outer walls are made .55 m. thick, the division walls .44 m.

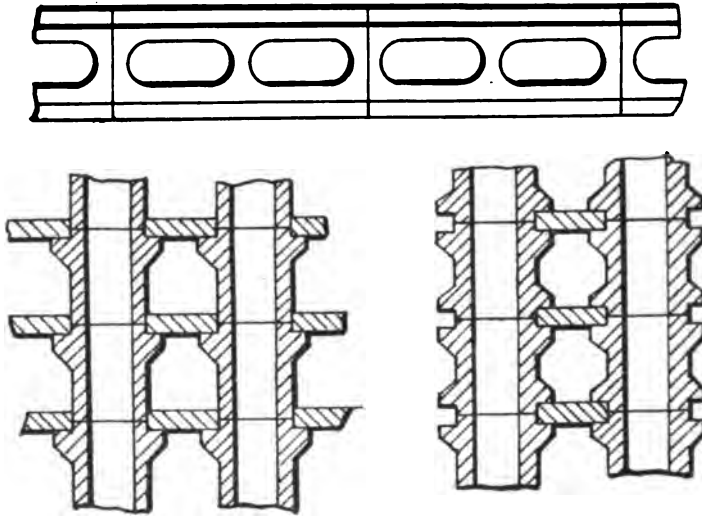


FIG. 80.—PERFORATED FIREBRICK BLOCKS FOR THE PARALLEL COUNTER-CURRENT SYSTEM OF HEAT RECUPERATION.

The width remaining for each chamber is

$$\frac{5.18 - (1.10 + .44)}{2} = 1.82 \text{ m.}$$

Each chamber has  $\frac{480}{2} = 240$  m. of perforated blocks.

The length of the chamber is 6.200 m. Each chamber will have 6 rows, 6.20 m. long, with 14 blocks in each, or for each meter of height  $6 \times 14 = 84$  running meters of perforated blocks.

Each row will then have a height of

$$\frac{240}{84} = 2.86 \text{ m.}$$

In order to use only full lengths of blocks we will take for the height the nearest common multiple of their length, 292 mm. or 2.920 meters.

Each chamber offers for the passage of the air 84 columns of perforated blocks, each with two perforations of .01251 sq. m. area, a total of

$$.01251 \times 84 = 1.05 \text{ sq. m.}$$

The flue distributing the secondary air to the perforation should have a cross-section 50% larger than this, or

$$\frac{1.05 \times 3}{2} = 1.59 \text{ sq. m.}$$

The width of the chamber is 1.82 m. Height of flue

$$\frac{1.59}{1.82} = .875 \text{ m.}$$

Volume of the air at 480° C. for each chamber,

$$.350 \times 2.7616 = .967 \text{ cu. m.}$$

Mean velocity of the air through the perforations,

$$\frac{.967}{1.05} = .92 \text{ m.}$$

—a good velocity for small rough tubes.

Volume of the air at 930° C.,

$$.350 \times 4.4131 = 1.544 \text{ cu. m.}$$

For the proper distribution of the air in the hearth 11 ports per side are needed. For practical use they are made .150 × .150 mm.

The velocity of the heated air issuing through them is

$$\frac{1.544}{11 \times .150 \times .150} = 6.24 \text{ m. per second.}$$

The same number of gas-ports are placed alternating with the air-ports, 11 per side. The gas issuing through the ports has a temperature of 400° C.

Volume of gas per side, at 400° C.,

$$\frac{.4845}{2} \times 2.468 = .598 \text{ cu. m.}$$

For the sake of simplicity in construction, the gas-ports are made of the same size as the air-ports.

Velocity of the gas issuing through the ports,

$$\frac{.598}{11 \times .150^2} = 2.41 \text{ m. per second.}$$

Owing to the pressure with which the gas comes from the producers, its velocity is much higher than that indicated by its volume and its temperature of 400° C. and the atmospheric pressure. In practice it is found that the gas velocity is higher than that of the air.

The air is to be sent through the recuperator by means of a fan; this allows for a simple and efficient regulation of the volume required.

Following is a calculation of the velocity of the products of combustion through the recuperators.

Volume of the products of combustion per side, their mean temperature through the recuperator being 870° C.,

$$\frac{1.343}{2} \times 4.1929 = 2.82 \text{ cu. m.}$$

In order to secure a thorough contact of the blocks with the products of combustion throughout the recuperator, they are made to circulate in three consecutive horizontal paths (see Fig. 33 and 35), on their way to the stack-flue.

Thus only one-third of the available space of the recuperator is usable at one time.

In each chamber we have passages 6.20 m. long by .182 m. wide and 259 mm. high. There are 50 such passages; the total volume, then, is

$$6.20 \times .182 \times .259 \times 50.$$

And as only one-third is available, the volume is,

$$\frac{6.20 \times .182 \times .259 \times 50}{3} = 4.87 \text{ cu. m.}$$

Mean velocity of the waste products through the recuperator,

$$\frac{4.87}{2.82} = 1.73 \text{ m. per second.}$$

The methods and formulas used in the calculation of the proper radiating areas to be taken for the absorption by air of a given number of calories can be made use of for all engineering problems involving the same factors.

If, instead of a firebrick recuperator, we had chosen to select, for lower temperatures, cast-iron pipes, the radiation and conduction coefficient of cast iron would have been introduced into the formula.

It is often desired to find the length of pipe required to cool to a known temperature a gaseous mass, traveling in cast-iron, wrought-iron or lead pipes. The same formulas will apply by making use of the proper coefficients.

## CHAPTER XVIII.

### REVERSING VALVES.

There are a large number of types of valves in use, from the original Siemens valve to the modern water-seals. A good valve should be such that it will preserve its true form, no matter to what range of temperature it is exposed. Cast-iron valves, when first made, may have perfect bearing surfaces; these are not preserved long, however, as the cast iron expands unequally, according to the shape of the casting, and the resulting distortion prevents the valve

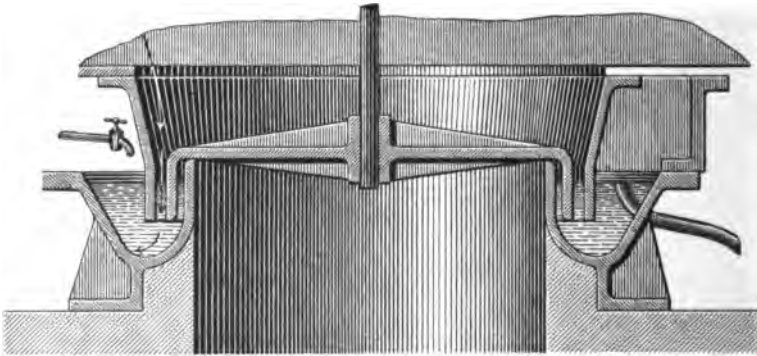
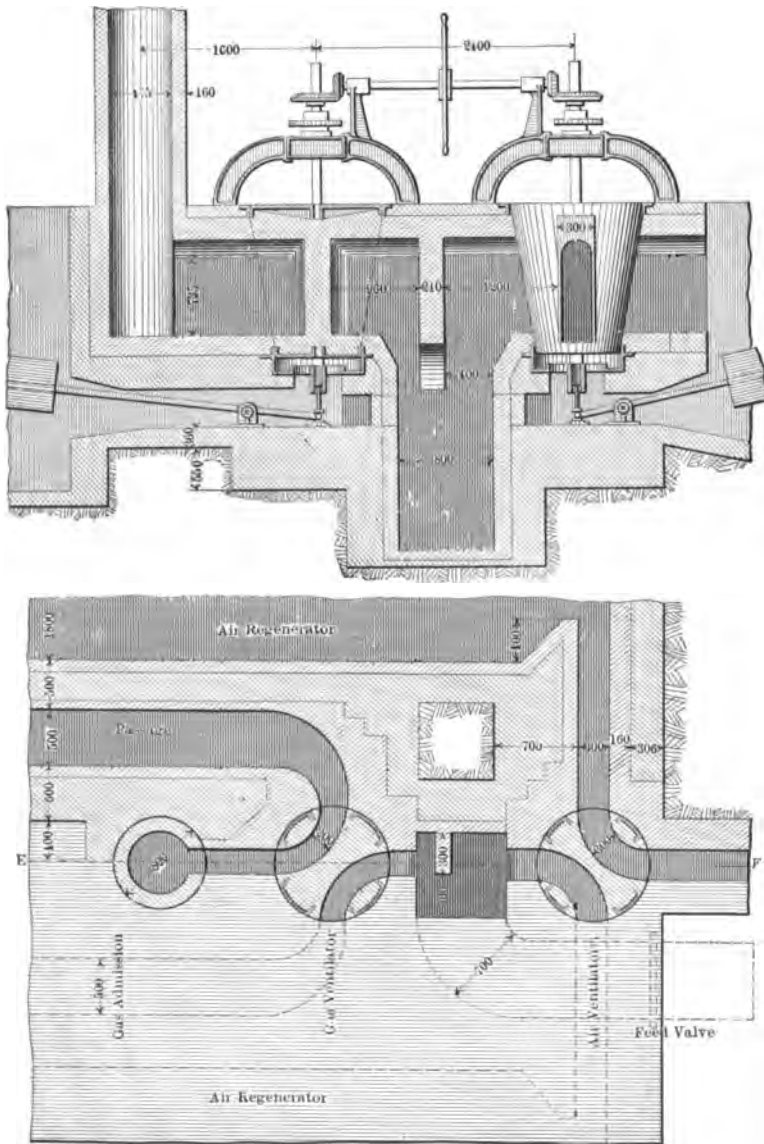


FIG. 81.—WAILES WATER-SEALED VALVE.

from fitting tight on its seat. Once the valve has become warped, it should be removed at once, as its condition will become worse on account of the high temperature caused by the gas burning at the leak. Also small amounts of dust, soot, etc., settling on the seat, will prevent tight closing. The seats should be selected with the view of avoiding the settling of solid particles, and should be self-cleaning.

The only valves that remain tight at all temperatures are the water-seal valves, providing that the level of the seal is kept hor-



**FIG. 82.—REVERSING VALVE.**  
**From F. Toldt, "Regenerativ Gasöfen."**

izontal. They have one grave defect, however, that of vaporizing a large quantity of water, the vaporization being a function of the temperature of the gas passing through the valves. This increase in the water vapor has an unfavorable effect on the thermic efficiency of the furnace, and in the case of steel furnaces may cause increased oxidation of the metallic bath.

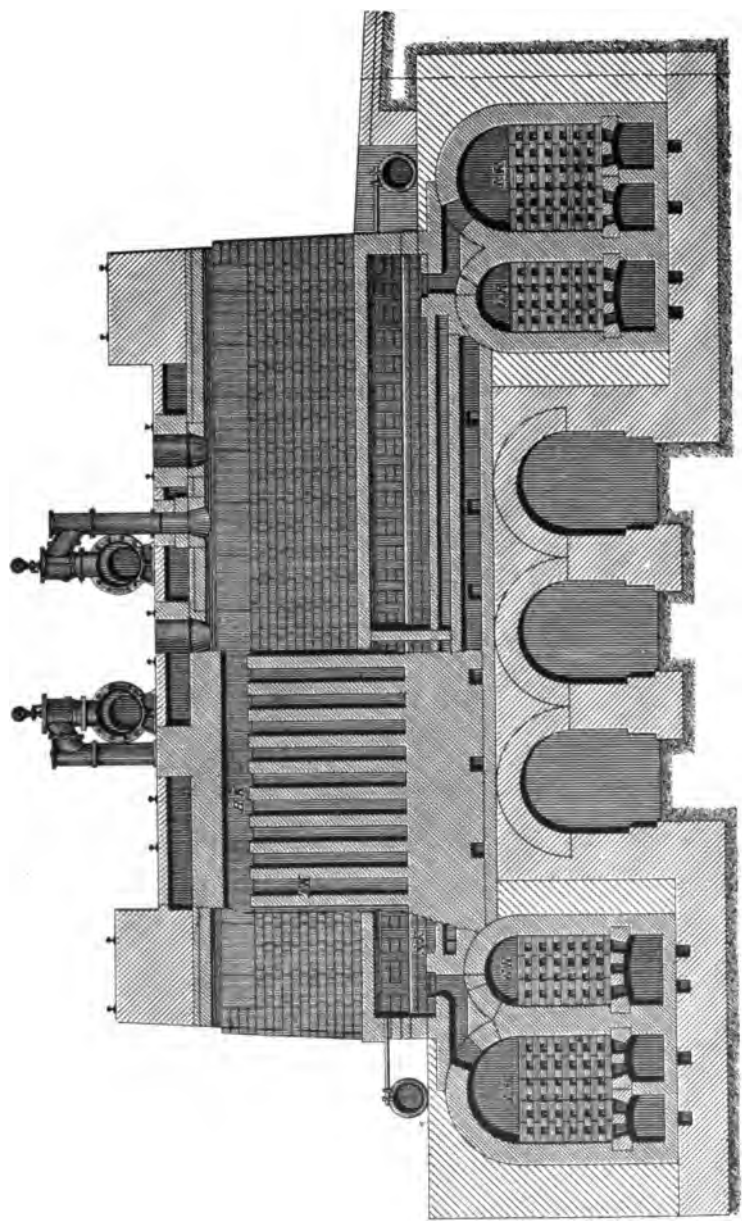


FIG. 83.—FORTER WATER-SEALED REVERSING VALVE, HAND-OPERATED, WITH CASING RAISED, SHOWING HOOD AND WATER-SEAL.

For most purposes, water-seal valves are to be preferred. Important leaks of gas are sometimes caused by dry valves, a portion of the producer-gas short-circuiting to the stack.

As an instance, we have the following sample of stack gas taken from a zinc furnace in which it was intended to use a thoroughly oxidizing flame:





From L. Toldt, *loc. cit.*

FIG 84.—COKE OVEN.

	% by Volume	% by Weight
CO <sub>2</sub> .....	13.75	20.21
CO.....	2.50	2.34
O <sub>2</sub> .....	3.75	4.01
H <sub>2</sub> .....	1.93	0.13
N <sub>2</sub> .....	78.07	73.31
H <sub>2</sub> O.....	4.50	.....

Entailing a dead loss of 16.67% of the fuel used.

It is well to have the gas inlet and the reversing valves distinct, the inlet valves being removed from the high temperature of the reversing valves.

#### HEARTH.

In the original Siemens furnace the roof is depressed, as it was thought necessary to bring the flames to impinge on the material to be heated on the hearth. This form has very serious drawbacks, among which are the rapid deterioration of the roof and the incomplete combustion of the gases.

In a furnace of so small a volume the velocities of the gaseous masses are so great that, notwithstanding the high rate of diffusion between the highly heated gases, they reach the ports of exit before complete combustion takes place. Furthermore, this disposition compels the gases to distribute themselves in thin blade-like streams, which burn only at their surface of contact.

Friedrich Siemens strongly advocates high, dome-shaped roofs, claiming that heating should be obtained by radiation. This form is doubtless the best for bituminous producer-gas, and in general producer-gases rich in illuminants. For producer-gas made from coke, anthracite or charcoal, a high roof would not be economical in fuel, as the flame is not very luminous.

It is well known that the contact of relatively cold materials cools the gases below their ignition points, thus promoting incomplete combustion.

In industrial operations, however, it is the ultimate economy which is the only important one. While the heating by radiation may be conducive to fuel economy, the time of melting, as claimed by H. H. Campbell,<sup>1</sup> is reduced by making the flame impinge on the stock.

<sup>1</sup> H. H. Campbell, *loc. cit.*, page 213.

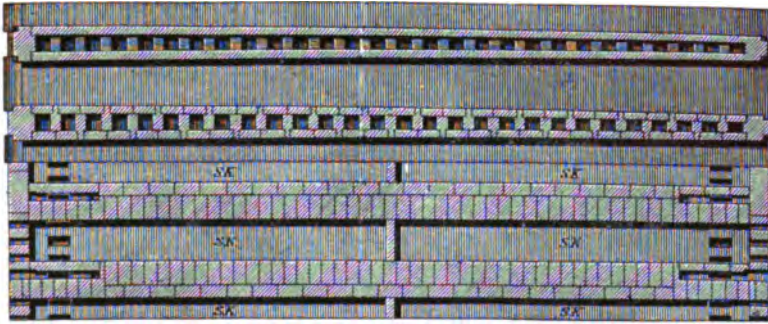


FIG. 84a.—COKE OVEN.  
From F. Toldt, *loc. cit.*

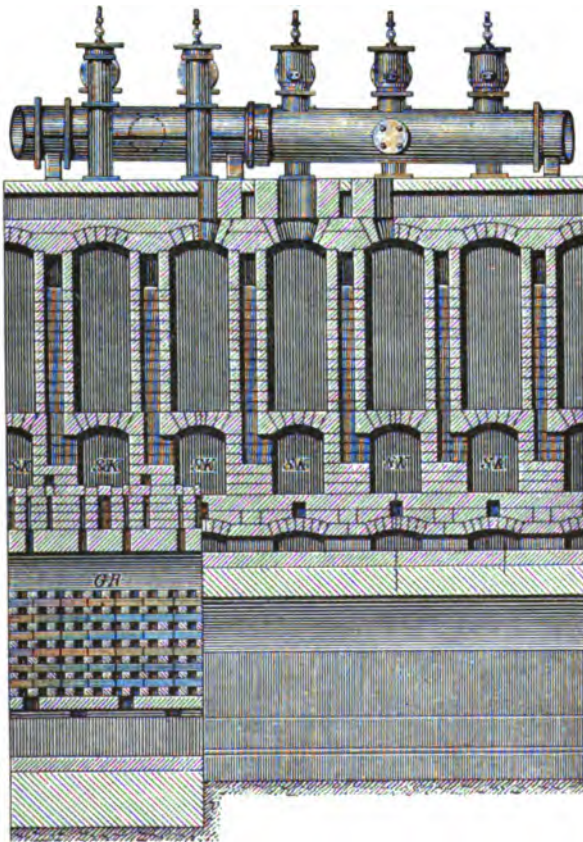


FIG. 84b.—COKE OVEN.  
From F. Toldt, *loc. cit.*

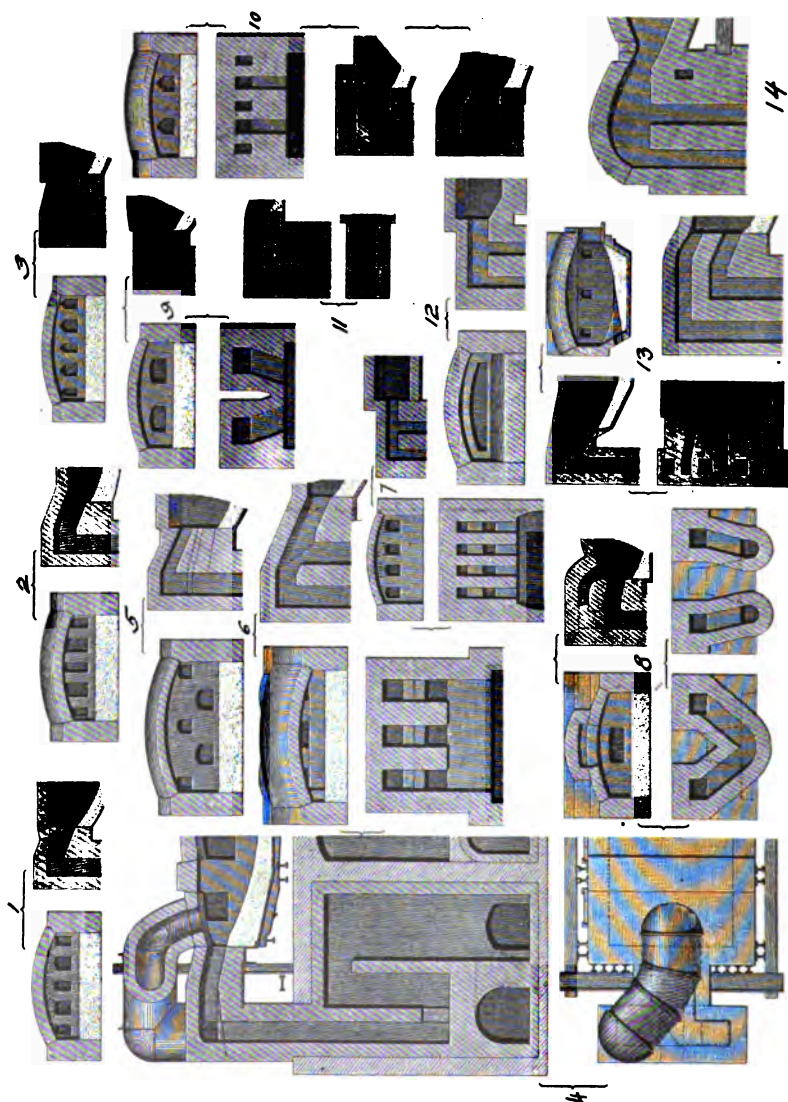


FIG. 85.—VARIOUS TYPES OF GAS AND AIR PORTS.

From F. Toldt, *loc. cit.*

Under American conditions it is of more importance to reduce the time of melt, thereby increasing the furnace capacity per day, than to save some fuel, while the reverse is probably true on the Continent, where fuel is very expensive and labor comparatively cheap.

The tendency of the present practice in the United States is to have a slight rise in the roof. However, many furnaces have a practically straight roof along a median line, passing through the hearth's longer axis (see Fig. 39). Roofs built along these lines are long-lived, as they are not cut by the flames.

The volume of the hearth should be such as to allow the velocities of the gases to decrease very materially as they issue from the ports, allowing the products of combustion to remain as long as practicable in the hearth. The increase in the time of sojourn permits complete combustion, as it affords a better opportunity for the diffusion to take place.

#### PORTS.

Many designs and dispositions of ports have been advanced, most of them quite complicated. With the gas and the air highly pre-heated, it is not necessary to go into great refinements of construction in order to secure complete combustion.

It is to be remembered that the ports have to withstand the most severe conditions, and that, above all, their construction should be such as to allow of long life and quick repairs.

The suggestions first brought forward by Siemens are still good. He recommended that the gas be prevented from coming in contact with either the roof or the furnace sides, the air-ports, therefore, to be placed above the gas-ports and overlapping these at both ends (No. 5, 10, and 13, Fig. 85).

In Fig. 85 are given several dispositions of ports. For small furnaces, the ports should either be inclined toward each other, or the air-ports given a sharp angle toward the gas-ports (No. 4 and 8, Fig. 10). The point of intersection of the gas and air currents should neither be too near the ports, as it would endanger their lives, nor too far, as the combustion would hardly have begun before the flame would meet the hearth material.

For large furnaces (50 to 70 tons) the air-port is given only a

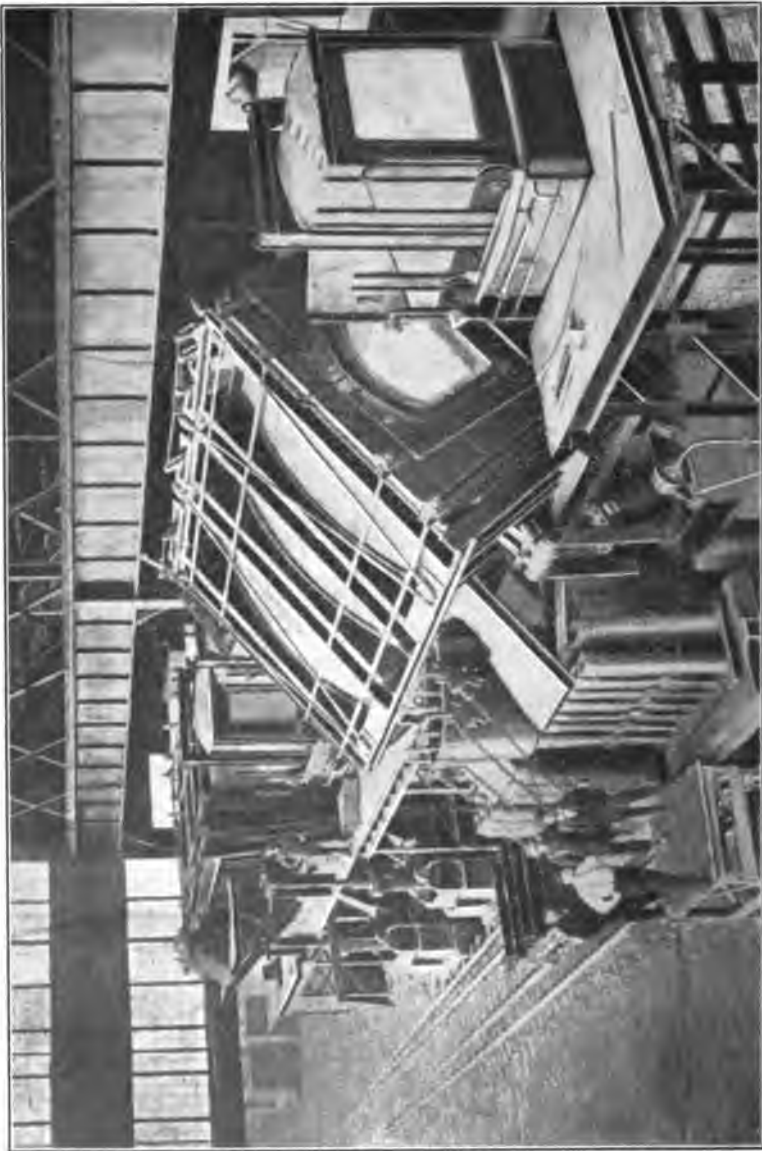


FIG. 88.—WELLMAN TILTING FURNACE, SHOWING THE INDEPENDENTLY BRACED PORT BLOCKS.

slight angle toward the gas-port. The present practice in America for these large furnaces is to have two ports only, one for the air and the other for the gas, the air-port overlapping the gas-port at each end.

In the Schoenwalders furnace, the gas and air meet in a combustion chamber preceding the hearth; this chamber and the ports themselves must be exposed to extreme temperatures; the loss by radiation is very high, and serves no good purpose.

In order to increase the length of the campaign of open-hearth furnaces, inventors have sought to enclose the ports, with their sub-dividing walls, in a removable cage with its own system of tie-rods and braces. This construction allows the removal of a block needing repair and its replacement in about an hour's time. The design of the block shown in Fig. 39 is that of C. E. Stafford.

Fig. 86 shows the construction of the self-contained, removable port-blocks of a tilting Wellman furnace.

The introduction of air-cooled cast-iron blocks under the ports also tends to lengthen the life of the port-blocks. In the case of tank glass furnaces (Fig. 38), or with muffle furnaces, where the flames have to heat a very large hearth at a uniform temperature, the ports are alternated, being placed side by side, or better in two horizontal rows, and are all built with horizontal sides, in order to have a gradual diffusion. The construction shown in Fig. 32 would tend to create an intense combustion at the zone of intersection of the two currents, which would endanger the life of a vessel in close proximity.

The conditions necessary to insure complete combustion, in the opinion of Ledebur,<sup>1</sup> are as follows:

- (1) High temperature in the combustion chamber.
- (2) Intimate mixture of the gases and air.
- (3) Diffusion of the chemically reacting gases.
- (4) Excess of oxygen.

All these conditions are practically met in modern metallurgical furnaces.

<sup>1</sup> Ledebur, "Die Gasfeuerungen."



## CHAPTER XIX.

### POWDERED FUEL.

Whenever practical, the use of powdered fuel offers considerable economy over direct or gas firing. The heat obtained is also more intense than that which can be obtained from either solid coal or producer-gas if care is taken to pre-heat the air required for combustion.

Dust-coal firing has the further advantage over gas furnaces of doing away with the gas-producer and its inherent losses. These are considerable, for it is seldom that the average thermic loss, in the gasification of the fuel by premature combustion to carbon dioxide, heat radiation and convection, is under 20% of the available calories; to this should be added the loss due to the carbon contained in the ash and the coal consumed in the boiler grate for the production of the steam required for the gas-producer. A total loss of 30% is a conservative figure for good practice.

With coal-dust firing there is only one combustion, that to  $\text{CO}_2$ ; further, the combustion is complete, the ash being free from residual carbon. The air required for combustion is also susceptible of close regulation, it being added in proper volumes and at the same time, mixed with the fuel.

The preparation of the powdered fuel, however, is a serious matter. For proper combustion the coal must be crushed and comminuted so that 95% of it will pass through a 100-mesh screen. Previous to crushing the coal must be freed from all moisture.

After going through a rotary drying kiln, the coal is sent to a tube-mill, half filled with French and Danish flint pebbles, 2 to 7 cm. in diameter. The grinding and screening take place jointly. From the tube-mill the fine dust is conveyed to the furnace.

When reduced to such fineness and kept dry, coal-dust will flow very much as a liquid. There is very little danger of the dust clogging up pipes or hanging in hoppers, etc.



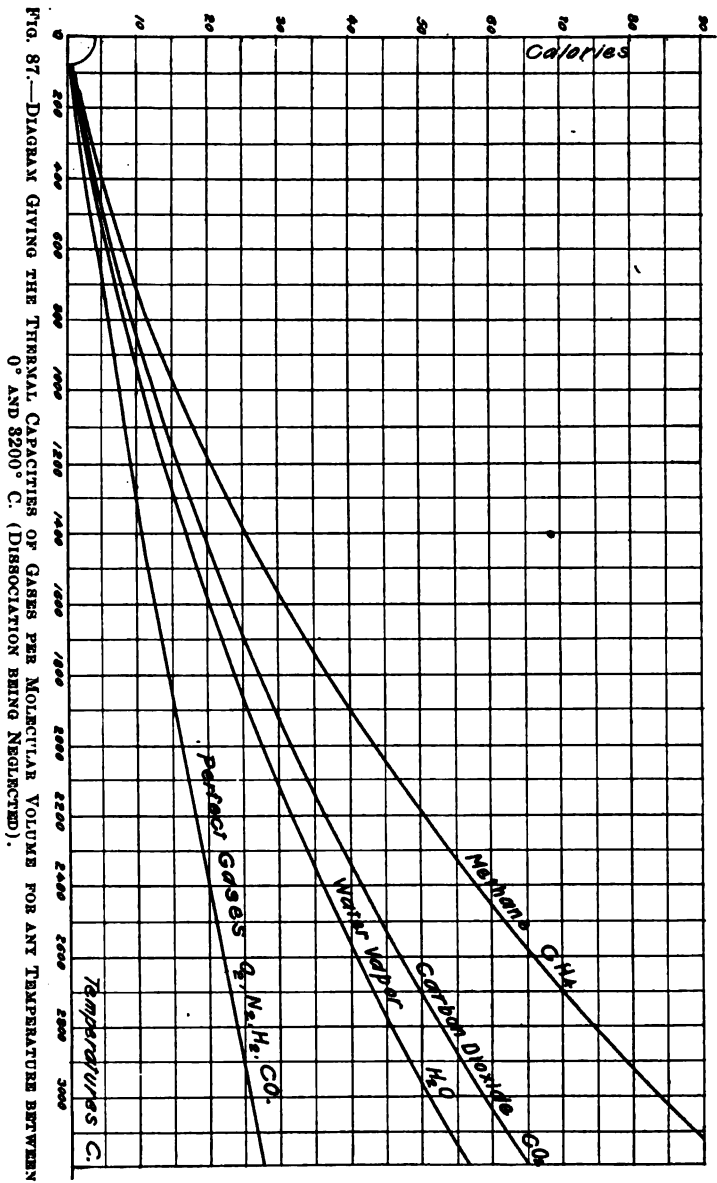


FIG. 87.—DIAGRAM GIVING THE THERMAL CAPACITIES OF GASES PER MOLECULAR VOLUME FOR ANY TEMPERATURE BETWEEN  $0^\circ$  AND  $3200^\circ$  C. (DISSOCIATION BEING NEGLECTED).

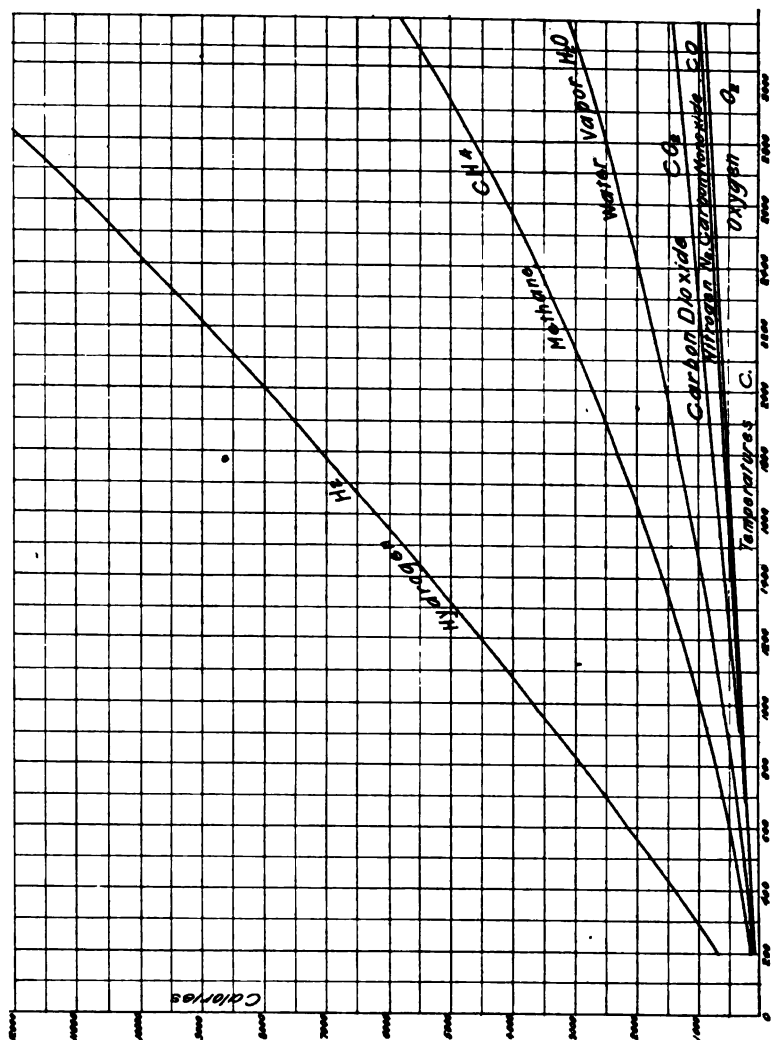


FIG. 88.—DIAGRAM GIVING THE THERMAL CAPACITIES OF GASES PER KILOGRAM FOR ANY TEMPERATURE BETWEEN  $0^{\circ}$  AND  $3200^{\circ}$  C. (DISSOCIATION BEING NEGLECTED).

The danger of a subsequent explosion, due to the ignition of coal-dust, has been largely overestimated. Since a terrible coal-dust explosion took place, in the grinding-mill of a cement company, care has been taken to avoid the accumulation of the powdered coal on the floors, and also to provide sufficient ventilation. The main point to bear in mind is to avoid a confined place in which the coal-dust may become well mixed with air.

Powdered coal, while lying in a heap, will burn as *slowly* as so much punk; a *sudden* complete combustion, giving, by the practically instantaneous elevation of temperature, rise to destructive gas explosions, can only take place if the coal-dust is thoroughly mixed with air. Such conditions will prevail when the powdered fuel is carried along by an air current. The coal-dust explosions of dry coal mines occur under precisely such conditions. If an explosion, small or large, of fire-damp takes place, the thick layer of coal-dust covering the walls, timbers and floor is at once transported by the powerful air current, and a secondary explosion may take place in the fuel cloud, which may prove more disastrous than the primary one. The same thing may occur with any combustible material, as flour, etc. Practically all the cement produced in the United States, outside of the natural gas or oil fields, is burned with coal-dust, and explosions are rarely heard of.

Dust-coal firing is admirably adapted to the obtention of high temperatures in long hearths. The pre-heating of the air required for combustion gives rise to a particular difficulty with regard to the ash-dust carried by the waste products.

The regenerator should be designed with generous ash-settling chambers and large passages in the checkerwork to prevent their undue contraction by the accumulation of ash-dust; at the same time the total area should not be so large as to cause the velocity of the gaseous currents to become too small, this tending to increase the ash-dust deposition.

The parallel counter-current regenerators are well adapted for this purpose, for, as we have seen, besides avoiding the use of valves, it is possible to clean out the passages for the waste products by a jet of steam or compressed air, or even with small and sharp water-jets. Just enough water should be injected to have instan-

taneous vaporization; some qualities of firebrick will stand sudden cooling without spalling. For regenerators a design similar to that of blast-furnace hot stoves would be advantageous, these being formed of a series of thin solid walls; the cleaning would thus be much simplified. Such a chamber would resemble that of the Ferraris Zinc Gas Furnace, U. S. patent 714,685.

Coal-dust firing, like gas firing, requires for great efficiency that the combustion take place in a chamber in contact with highly heated material, firebrick being the best. A comparatively cool surface will cause a chilling of the fuel and air immediately in contact with it below the ignition point, resulting in incomplete combustion. It follows that, if dust firing is to be used in connection with boilers, a firebrick combustion chamber should be provided in order that only the oxidized waste products come in contact with the boiler flues.

The powdered coal may be supplied to the furnace in different ways, according to its dimensions. Practically the same remarks made in connection with gas firing apply to firing with coal-dust. For a small hearth, the fuel should be fed in a diffuse state, that is, already mixed with the air required for combustion. For long furnaces, as rotary cement kilns, roasters, driers, etc., the fuel should be sent axially under high velocity, the air being admitted by ports, parallel to the coal-dust port. A powerful elongated flame is created, the coal-dust burning practically the whole length of the furnace, which may be 150 ft. long.<sup>1</sup>

Coals rich in volatile matter, as gas coals and lignites, are to be preferred. The following analysis is a fair average of the West Virginia gas coals:

Fixed carbon .....	54.00%
Volatile matter.....	32.75
Ash.....	12.00
Moisture.....	1.25

With such coals, the combustion takes place practically in two stages. The coal as it emerges from the stoker is coked, the volatile matter being liberated and burned at once, while the solid coke is first brought to bright redness before it ignites. During these

<sup>1</sup> Rotary clinkering furnace of the Edison Portland Cement Company.

successive operations, the coal has traveled a large portion of the length of the furnace.

#### COAL-DUST STOKERS.

Few fields of industry have been more studied than the application of powdered fuel to furnace firing. On pages 283-286 is given a list of the United States patents covering the field. All are based on the injection, under pressure as high as 50 lb. and as low as 8 oz., of the air carrying with it the powdered fuel.

The greatest field of coal-dust firing is in the cement industry. Practically all of the cement produced in the United States is made in rotary kilns, and this type is fast superseding all other forms abroad. The rotary cement kiln has not a high thermic efficiency; its simplicity of operation and large capacity, however, make it on the whole very economical. Its thermic efficiency is low, for the following reasons:

- (1) High velocity of the gases rushing through it.
- (2) Large excess of air, there being a number of openings some of which cannot be closed, such as the necessary clearance space between the terminal hoods and the kiln proper.
- (3) Practically no air recuperation.
- (4) High radiation of the metallic wall.
- (5) High temperature of the issuing clinker.

The radiation is unavoidable, and, furthermore, necessary, the life of the shell depending on it. The efficiency can be increased only by reducing the losses due to the excess of air and by recuperation. A number of recuperators have been proposed; most of them, however, are faulty in principle and cannot give good air recuperation.

Rotary kilns are built with a second rotary kiln lying in the same or in the reverse direction. The cement mixture enters the upper kiln, the clinker being discharged into the second. An air current is made to pass in a reverse direction, first through the lower kiln, then through the upper, to the combustion of the fuel. In long kilns, 5 to 8 ft. in diameter, the heated air will rush along

the upper surface, while the hot clinker occupies the lower part. The heating of the air can be done only through direct contact, not by radiation. The air is in contact only with the shell of the kiln, which is in turn heated by contact with the clinker. The calories carried away by the white clinker form a large percentage of the fuel used.

The following example is taken from practice:

A rotary kiln producing 200 bbl. of clinker (weight of a barrel is 173 kg.) per 24 hours consumes 54.5 kg. of fuel per bbl. The clinker leaves the kiln at a temperature of 1300° C. Taking the specific heat of cement clinker to be, at that high temperature, .30, the calories contained in the clinker produced daily are

$$173 \times 200 \times .30 \times 1300 = 13,494,000 \text{ calories.}$$

The analysis of the coal is given, page 274.

The calorific power of the coal can be found by means of Goutal's formula (see page 222).

$$\begin{aligned} V' &= \text{Volatile matter, neglecting ash and moisture.} \\ &= \frac{100 \times 32.75}{86.75} = 37.75\%. \end{aligned}$$

From the table of factors:

$$a = 85.75 \text{ calories.}$$

Substituting in Goutal's formula,

$$\text{Calorific power} = 82 \times 54 \times 85.75 \times 37.75 = 7665 \text{ cal.}$$

The calories contained in the clinker are equivalent to

$$\frac{13,494,000}{7665} = 1760 \text{ kg. of coal.}$$

The kiln consumes per day,  $54.5 \times 200 = 10,900$  kg.

The calories carried away by the hot clinker are equivalent to

$$\frac{1760 \times 100}{10,900} = 16.14\%.$$

A rather important percentage of the total available calories.

It is necessary to cool the clinker for handling. This is usually done by first quenching it with water, and then finishing the cooling by air currents. For the latter treatment, the clinker is stacked in an iron tower, with baffle plates, the air being forced to go through the clinker piles on its way to the atmosphere, whence it passes as soon as it has been heated.

*Efficiency Test of a Rotary Clinkering Furnace for the Manufacture of Portland Cement.*

A rotary kiln 20 m. in length burns .131 kg. of powdered bituminous coal per second, and sinters .656 kg. of raw rock mixture in the same time. The whole of the ash in the coal is collected in the dust chamber, none contaminating the clinker.

*Analysis of the Products of Combustion.*

CO <sub>2</sub> .....	26.53%
O <sub>2</sub> .....	.....
CO.....	1.70
N <sub>2</sub> .....	71.77

Total.....	100.00
------------	--------

Water vapor.....	8.50%
------------------	-------

The elementary analysis of the coal is as follows:

Total carbon.....	76.5 %
Hydrogen.....	4.91
Ash.....	8.50

The analysis is given on dry basis; the coal carried 0.94% of moisture.

Calorific power (dry basis)..... 7804 calories.

Both the raw rock and the powdered coal were fed into the bins at a temperature of 52° C.

*Analysis of Raw Rock.*

Carbon dioxide.....	31.81%
Water.....	2.62
Graphite.....	1.05
Loss by ignition.....	35.48

Temperature of the products of combustion..... 800°

Temperature of discharged clinker..... 1320°

We will first find the total amount of calories brought in the furnace:

Kg. of dry coal burned per second,  $.9906 \times .131 = .1297$ .

Calories brought by coal,  $.1297 \times 7804 = 1012.7$ .

Kg. of graphite in raw rock,  $.656 \times .0105 = .00689$ .

Calories liberated by graphite,  $.00689 \times 8147 = 56.11$ .

Sensible heat brought by coal and rock, taking their specific heat as .21 for both,

$$(.656 + .131) \times .21 \times 52 = 8.6 \text{ calories.}$$

Total number of calories brought by the coal and the raw rock,  
 $1012.7 + 56.1 + 8.6 = 1077.4$ .

We will take the specific of the clinker to be .30 at the temperature of 1320°.

Clinker produced per second,  $.656 \times .6452 = .424$  kg.

Calories held by clinker at 1320°,

$$.424 \times .30 \times 1320 = 168.$$

Total weight of carbon brought by the rock and coal per second:

Carbon in coal,  $.1297 \times .765 = .0993$  kg.

Carbon as graphite, .00689

Carbon dioxide in rock,  $.656 \times .3181 = .209$ .

Carbon in carbon dioxide,  $\frac{12 \times .209}{44} = .057$  kg.

Total carbon,  $.0993 + .0069 + .057 = .1632$  kg.



One cubic meter of waste products at 0° and 760 mm. pressure contained 265.3 liters of carbon dioxide, weighing

$$.2653 \times 1.96503 = .52132 \text{ kg.}$$

$$\text{holding } \frac{12 \times .52132}{44} = .1422 \text{ kg. of carbon.}$$

The 17 liters of carbon monoxide weighed

$$.017 \times 1.2505 = .02126 \text{ kg.}$$

$$\text{and contained } \frac{12 \times 21.26}{28} = .0091 \text{ kg. of carbon.}$$

Total weight of carbon per c.m. of waste products,

$$.1422 + .0091 = .1513 \text{ kg.}$$

Since we have accounted for all of the carbon entering the furnace, it becomes possible to calculate the volume of the waste products issuing from the stack, per second:

$$\text{Volume of dry gases } \frac{.1632}{.1513} = 1.08 \text{ c.m.}$$

$$\text{Volume of wet gases, } 1.08 \times 1.085 = 1.17 \text{ c.m.}$$

Weight of the water vapor, per second,

$$.085 \times 1.08 \times .80405 = .0737 \text{ kg.}$$

Total weight of carbon dioxide, per second,

$$.52132 \times 1.08 = .56232.$$

Calories contained in .56232 kg. of carbon dioxide at 800°:

From Table 5 we find the thermal capacities per kilogram,

$$.562 \times 208 = 117. \text{ calories.}$$

Weight of nitrogen in 1.08 c.m.,

$$1.2544 \times .7177 \times 1.08 = .9711 \text{ kg.}$$

Weight of the carbon monoxide:

$$1.2505 \times .017 \times 1.08 = .023 \text{ kg.}$$

Thermal capacities of carbon monoxide and nitrogen at 800°,  
207 calories.

Calories held by the nitrogen and carbon monoxide,

$$(.9711 + .023) \times 207 = 205.76 \text{ calories.}$$

Latent calories held in .023 kg. of carbon monoxide,

$$.023 \times 2403 = 55.10 \text{ calories.}$$

Calories held by the water vapor, 461 calories per kg. at 800°,

$$.0737 \times 461 = 33.98 \text{ calories.}$$

Total number of calories, latent and sensible, lost,

$$117. + 205.76 + 55.10 + 33.98 = 411.84 \text{ calories.}$$

According to our definitions of lost and utilized heats we have:

Heat lost through the stack (sensible and latent),

$$\frac{411.84 \times 100}{1077.4} = 38.22\%.$$

Heat lost through incomplete combustion (latent heat),

$$\frac{55.10 \times 100}{1077.4} = 5.11\%.$$

Heat carried away by the clinker,

$$\frac{168 \times 100}{1077.4} = 15.60\%.$$

Heat utilized in the furnace, per difference, 46.18%.

What volume of air was injected in the kiln?

The total weight of carbon burned per second is .1022 kg., of which .0098 kg. was burned as carbon monoxide and the remainder, .0924, as carbon dioxide.

One kg. of carbon burning to carbon dioxide requires 9.02 c.m. of air (Table 2).

Volume of air required by the carbon burning to carbon dioxide,

$$9.02 \times .0924 = .8334 \text{ c.m.}$$

One kg. of carbon burning to carbon monoxide requires 4.48 c.m. of air; the volume required for .0098 is

$$4.48 \times .0098 = .044 \text{ c.m.}$$

Weight of hydrogen burned per second,

$$.0491 \times .1295 = .00637 \text{ kg.}$$

One kilo of hydrogen requires 26.88 c.m. of air.

Volume of air required for the hydrogen,

$$.00637 \times 26.88 = .1712 \text{ c.m.}$$

Total volume of air,

$$.8334 + .044 + .1712 = 1.0486 \text{ c.m.}$$

The inner cross-section of the kiln being 1.824 sq.m., what is the mean velocity of the gases through the barrel?

The temperature of the gases near the discharging point of the clinker is 1340°:

$$\text{Mean temperature } \frac{1340 + 800}{2} = 1070^\circ.$$

Volume of the waste products at 1070° (Table 19):

$$V' = V (1 + \alpha t) = 1.17 \times 4.9269 = 5.766 \text{ c. m.}$$

Mean velocity, in meters:

$$\frac{5.766}{1.824} = 3.16 \text{ m.}$$

By increasing the length of the kiln from 20 to 40 meters the temperature of the waste products has been lowered to 300°. What percentage of heat will then be lost through the stack, and what will be the resulting economy?

At 300° the thermal capacities of the carbon dioxide, carbon monoxide, nitrogen and water vapor are respectively:

68.1, 76 and 153 calories.

By using the weights found previously we have a total loss in calories, through the stack, of 125.14.

$$\% \text{ of heat lost } \frac{125.14 \times 100}{1077.40} = 11.61\%,$$

a difference of

$$38.22 - 11.61 = 26.61\%.$$

Through proper recuperation of the calories carried away by the clinkers (15.60% of the total available calories), it is possible to bring back in the furnace, as heated air, about 10% of that lost heat. Thus, by proper kiln dimensions and recuperation, a total saving of 36% can be effected.

## CHAPTER XX.

### LIST OF U. S. PATENTS COVERING THE STOKING OF POWDERED FUEL.

53,208—March 13, 1866. Improved Method of Burning Waste Coal. J. D. Whelpley and Jacob J. Storer.

Reissue 3,857—March 1, 1870. Improvement in the Use and Application of Fuel in Metallurgic and Other Furnaces. J. D. Whelpley and Jacob J. Storer.

103,695—May 31, 1870. Improvement in Feeding Fuel to Metallurgic and Other Furnaces. J. D. Whelpley and Jacob J. Storer.

103,804—May 31, 1870. Improvements in Feeding Powdered Fuel to Metallurgic and Other Furnaces. J. D. Whelpley and Jacob J. Storer.

111,614—Feb. 7, 1871. Improvement in Apparatus for Feeding Pulverized Coal to Furnaces. Thomas Russel Crampton.

111,615—Feb. 7, 1871. Improvement in Apparatus for Distributing and Feeding Powdered Fuel to Furnaces. Thomas Russel Crampton.

111,616—Feb. 7, 1871. Improvements in Furnaces for Burning Pulverized Fuel under Steam-Boilers, Evaporators, etc. J. D. Whelpley and Jacob J. Storer.

116,903—July 11, 1871. Improvement in Treatment of Ores by means of Fuel, Chemicals and Fluxes. J. D. Whelpley and Jacob J. Storer.

120,007—Oct. 17, 1871. Improvement in Apparatus for Feeding Fuel into Furnaces. John Y. Smith.

120,008—Oct. 17, 1871. Improvement in Apparatus for Feeding Pulverized Fuel to Metallurgical and Other Furnaces. John Y. Smith.

120,680—Nov. 7, 1871. Improvement in Apparatus for Feeding Pulverized Fuel to Furnaces. John Y. Smith.

184,122—Nov. 7, 1876. Improvement in Pulverized Fuel Feeder for Smelting-Furnaces. William West.

185,592—Dec. 19, 1876. Improvement in Apparatus for Introducing Powdered Fuel into Furnaces. George K. Stevenson.

227,176—May 4, 1880. Feeder for Pulverized Fuel. John G. McAuley and William West.

234,395—Nov. 16, 1880. Hydrocarbon-Furnace. William D. Dickey.

238,891—March 15, 1881. Device for Feeding Fine Fuel. Augustin Greiner.

240,265—Apr. 19, 1881. Apparatus for Feeding Fuel. Charles H. Palmer.

243,593—June 28, 1881. Furnace. John G. McAuley.

245,427—Aug. 9, 1881. Mechanism for Feeding Fine Fuel. John D. Averell.

247,570—Sept. 27, 1881. Fuel-Feeding Apparatus. John G. McAuley.

261,864—Aug. 1, 1882. Feeding Light Fuel. Henry Mason.

265,347—Oct. 3, 1882. Burning Pulverulent Fuel. Ernest Tourangin.

292,237—Jan. 22, 1884. Apparatus for Feeding and Consuming Fine Fuel. Julius Leede.

295,145—Mar. 18, 1884. Coal-Dust Feeder. Henry A. Bradley.

317,712—May 12, 1885. Hydrocarbon Injector. William W. Brisben.

327,210—Sept. 29, 1885. Feeding Fine Fuel. William Westlake.

332,975—Dec. 22, 1885. Feeding Fuel to Boilers. Samuel W. Valentine.

338,105—Mar. 16, 1886. Feeding Fine Fuel. William Rogers.

406,753—July 9, 1889. Apparatus for Burning Culm. Allan Mason.

411,555—Sept. 24, 1889. Apparatus for Burning Coal and Hydrocarbon Fuel in Combination. Allan Mason.

414,322—Nov. 5, 1889. Coal-Dust Feeder. Edmond Pait.

438,852—Oct. 21, 1890. Apparatus for Burning Coal and Hydrocarbon Fuel in Combination. Allan Mason.

457,589—Aug. 11, 1891. Rotary Furnace for Burning Cement, Lime, etc. Jose F. De Navarro.

- 464,514—Dec. 8, 1891. Rotary Furnace for Burning Cement. Jose F. De Navarro.
- 475,715—May 24, 1892. Firing Apparatus for Use with Coal-Dust. Carl Wegener.
- 494,375—Mar. 28, 1893. Pulverized Fuel Feeder. Hugh S. Grigsby.
- 510,788—Dec. 12, 1893. Pulverized Fuel Burner. Frederick H. Hawkins.
- 511,004—Dec. 19, 1893. Firing Apparatus for Use with Coal-Dust. Carl Wegener.
- 516,652—Mar. 20, 1894. Fine-Fuel Furnace. Hermann Kluepfel.
- 517,632—Apr. 8, 1894. Fine-Fuel Furnace. Carl Wegener.
- 519,784—May 15, 1894. Coal-Dust Firing Apparatus. Carl Wegener.
- 524,579—Aug. 14, 1894. Fuel-Feeding Device. Joseph Davies.
- 531,160—Dec. 18, 1894. Apparatus for Burning Granular Fuel. Colin W. Claybourne.
- 537,108—Apr. 9, 1895. Coal-Dust Feeder for Furnaces. Alfred Friedeberg.
- 540,114—May 28, 1895. Method of and Apparatus for Mixing Coal-Dust and Air for Combustion. Constanz Schmitz.
- 551,074—Dec. 10, 1895. Feeding Appliance for Coal-Dust. Ferdinand De Camp.
- 551,098—Dec. 10, 1895. Apparatus for Burning Fine Fuel. William Melvin Russel.
- 553,696—Jan. 28, 1896. Fuel-Burner. Gamaliel C. St. John.
- 554,327—Feb. 11, 1896. Coal-Dust Firing Apparatus. Carl Wegener.
- 558,875—Apr. 21, 1896. Apparatus for Burning Coal-Dust. Georg Hillinger.
- Reissue 11,816—Apr. 3, 1900. Apparatus for Burning Coal-Dust. Georg Hillinger.
- 558,875—Apr. 21, 1896. Apparatus for Burning Coal-Dust. Georg Hillinger.
- 563,789—July 14, 1896. Feeding Pulverized Fuel. Edward C. mith.

568,599—Sept. 29, 1896. Method of and Apparatus for Calcining Cement. Clifford Bonneville.

571,139—Nov. 10, 1896. Fuel-Feeder for Furnaces. Wilhelm Ruhl.

577,995—Mar. 2, 1897. Furnace for Burning Coal-Dust. Gustav Unger.

581,244—Apr. 20, 1897. Apparatus for Feeding Comminuted Fuel to Furnaces. Charles J. Allen and Frank R. Tibbitts.

582,587—May 11, 1897. Apparatus for Utilizing Heat of Furnace Products. Alexander Marshall Hay.

626,981—June 13, 1899. Feeding Device for Steam-Boiler Furnaces. Joseph Davies.

645,031—Mar. 6, 1900. Apparatus for Burning Pulverized Fuel. Edward H. Hurry and Harry J. Seaman.

658,069—Sept. 18, 1900. Method of Feeding Pulverized Fuel. Frederick H. Lewis.

661,700—Nov. 13, 1900. Apparatus for Burning Pulverized Fuel. Frederick H. Lewis.

691,337—Jan. 14, 1902. Apparatus for Feeding Fine Fuel. Rolla C. Carpenter.

759,356—May 10, 1904. Method of Burning Portland Cement Clinker, etc. Thomas A. Edison.

759,357—May 10, 1904. Apparatus for Burning Portland Cement Clinker, etc. Thomas A. Edison.



# TABLES.

## CHAPTER XXI.

TABLE 13

COMPOSITION IN WEIGHT OF THE ATMOSPHERIC AIR.

O <sub>2</sub>	N <sub>2</sub>	Air	O <sub>2</sub>	N <sub>2</sub>	Air	O <sub>2</sub>	N <sub>2</sub>	Air
0.1	0.33	0.43	3.3	11.05	14.35	20.0	66.96	86.96
0.2	0.67	0.87	3.4	11.39	14.79	21.0	70.26	91.26
0.3	1.00	1.30	3.5	11.72	15.22	22.0	73.56	95.56
0.4	1.34	1.74	3.6	12.06	15.63	23.0	77.00	100.00
0.5	1.67	2.17	3.7	12.39	16.09	24.0	80.16	104.16
0.6	2.01	2.61	3.8	12.72	16.52	25.0	83.56	108.56
0.7	2.34	3.04	3.9	13.06	16.96	26.0	86.96	112.96
0.8	2.68	3.48	4.0	13.40	17.40	27.0	90.36	117.36
0.9	3.01	3.91	4.1	13.73	17.83	28.0	93.76	121.76
1.0	3.35	4.35	4.2	14.06	18.26	29.0	97.12	126.12
1.1	3.68	4.78	4.3	14.40	18.70	30.0	100.48	130.48
1.2	4.02	5.22	4.4	14.74	19.14	31.0	103.84	134.84
1.3	4.35	5.65	4.5	15.07	19.57	32.0	107.20	139.20
1.4	4.69	6.09	4.6	15.40	20.00	33.0	110.54	143.54
1.5	5.02	6.52	4.7	15.74	20.44	34.0	113.88	147.88
1.6	5.36	6.96	4.8	16.08	20.88	35.0	117.22	152.22
1.7	5.69	7.39	4.9	16.41	21.31	36.0	120.56	156.56
1.8	6.03	7.83	5.0	16.74	21.74	37.0	123.90	160.90
1.9	6.36	8.26	6.0	20.04	26.04	38.0	127.34	165.24
2.0	6.70	8.70	7.0	23.44	30.44	39.0	130.58	169.58
2.1	7.03	9.13	8.0	26.80	34.80	40.0	133.92	173.92
2.2	7.37	9.57	9.0	30.14	39.14	41.0	137.22	178.22
2.3	7.70	10.00	10.0	33.48	43.48	42.0	140.56	182.56
2.4	8.04	10.44	11.0	36.78	47.78	43.0	143.82	186.82
2.5	8.37	10.87	12.0	40.08	52.08	44.0	147.12	191.12
2.6	8.71	11.31	13.0	43.48	56.48	45.0	150.56	195.56
2.7	9.04	11.74	14.0	46.88	60.88	46.0	154.00	200.00
2.8	9.38	12.18	15.0	50.24	65.24	47.0	157.16	204.16
2.9	9.71	12.61	16.0	53.60	69.60	48.0	160.32	208.32
3.0	10.02	13.02	17.0	56.94	73.94	49.0	163.73	212.72
3.1	10.38	13.48	18.0	60.28	78.28	50.0	167.12	217.12
3.2	10.71	13.91	19.0	63.62	82.62	60.0	200.96	260.96

TABLE 14

COMPOSITION IN VOLUMES OF THE ATMOSPHERIC AIR.

O <sub>2</sub>	N <sub>2</sub>	Air	O <sub>2</sub>	N <sub>2</sub>	Air	O <sub>2</sub>	N <sub>2</sub>	Air
0.1	.38	.48	3.3	12.56	15.86	20.0	76.16	96.16
0.2	.76	.96	3.4	12.94	16.34	21.0	79.97	100.97
0.3	1.14	1.44	3.5	13.32	16.82	22.0	83.78	105.78
0.4	1.52	1.92	3.6	13.70	17.30	23.0	87.58	110.58
0.5	1.90	2.40	3.7	14.08	17.78	24.0	91.39	115.39
0.6	2.28	2.88	3.8	14.46	18.26	25.0	95.20	120.20
0.7	2.66	3.36	3.9	14.85	18.75	26.0	99.01	125.01
0.8	3.04	3.84	4.0	15.23	19.23	27.0	102.82	129.82
0.9	3.42	4.32	4.1	15.61	19.71	28.0	106.62	134.62
1.0	3.81	4.81	4.2	15.99	20.19	29.0	110.43	139.43
1.1	4.19	5.29	4.3	16.37	20.67	30.0	114.24	144.24
1.2	4.57	5.77	4.4	16.75	21.15	31.0	118.05	149.05
1.3	4.95	6.25	4.5	17.13	21.63	32.0	121.85	153.85
1.4	5.33	6.73	4.6	17.52	22.12	33.0	125.66	158.66
1.5	5.71	7.21	4.7	17.89	22.59	34.0	129.47	163.47
1.6	6.09	7.69	4.8	18.27	23.07	35.0	133.28	168.28
1.7	6.47	8.17	4.9	18.65	23.55	36.0	137.09	173.09
1.8	6.85	8.65	5.0	19.04	24.04	37.0	140.90	177.90
1.9	7.23	9.13	6.0	22.85	28.85	38.0	144.70	182.70
2.0	7.61	9.61	7.0	26.66	33.66	39.0	148.51	187.51
2.1	7.99	10.09	8.0	30.46	38.46	40.0	152.32	192.32
2.2	8.37	10.57	9.0	34.27	43.27	41.0	156.13	197.13
2.3	8.75	11.05	10.0	38.08	48.08	42.0	159.93	201.93
2.4	9.13	11.53	11.0	41.89	52.89	43.0	163.74	206.74
2.5	9.51	12.01	12.0	45.69	57.69	44.0	167.55	211.55
2.6	9.89	12.49	13.0	49.50	62.50	45.0	171.36	216.36
2.7	10.27	12.97	14.0	53.31	67.31	46.0	175.17	221.17
2.8	10.65	13.45	15.0	57.12	72.12	47.0	178.98	225.98
2.9	11.03	13.93	16.0	60.93	76.93	48.0	182.78	230.78
3.0	11.42	14.42	17.0	64.74	81.74	49.0	186.59	235.59
3.1	11.80	14.90	18.0	68.54	86.54	50.0	190.40	240.40
3.2	12.18	15.38	19.0	72.35	91.35	60.0	228.48	288.48

TABLE 15

WEIGHTS AND SPECIFIC GRAVITIES OF GASES FOUND IN FURNACES.

Gas	Formula	SPECIFIC GRAVITY		Weight of 1 Lit. at 0° C. 760 mm., 45° Latitude and at Sea Level
		Hydrogen = 2, Mol. Weight	Air = 1	
Acetylene.....	C <sub>2</sub> H <sub>2</sub>	25.947	.89820	1.16143 Grms.
Atmospheric Air.....			1.00000	1.293052 "
Ethane.....	C <sub>2</sub> H <sub>6</sub>	29.947	1.03667	1.34047 "
Ethylene.....	C <sub>2</sub> H <sub>4</sub>	27.947	0.96744	1.25096 "
Carbon Monoxide.....	CO	27.937	0.96709	1.25050 "
Carbon Dioxide.....	CO <sub>2</sub>	43.900	1.51968	1.96508 "
Hydrogen.....	H <sub>2</sub>	2.000	0.069224	0.089523 "
Hydrogen Sulphide.....	H <sub>2</sub> S	34.000	1.17697	1.52189 "
Methane.....	CH <sub>4</sub>	15.974	0.55297	0.71502 "
Nitrogen.....	N <sub>2</sub>	28.024	0.97010	1.25440 "
Oxygen.....	O <sub>2</sub>	31.827	1.0521	1.43908 "
Sulphur Dioxide.....	SO <sub>2</sub>	63.927	2.21295	2.86146 "
Water Vapor.....	H <sub>2</sub> O	17.963	0.62182	0.80405 "

Landolt and Boernstein, *loc. cit.*, page 77.

TABLE 16

SPECIFIC HEATS PER MOLECULAR VOLUMES.

Gas	Under Constant Pressure	Under Constant Volume
Perfect Gases (O <sub>2</sub> , N <sub>2</sub> , H <sub>2</sub> , CO).	$6.83 \times 10^{-3} + 1.2 \times 10^{-6}$	$4.83 \times 10^{-3} + 1.2 \times 10^{-6}$
Water Vapor, H <sub>2</sub> O.....	$8.08 \times 10^{-3} + 5.8 \times 10^{-6}$	$6.08 \times 10^{-3} + 5.8 \times 10^{-6}$
Carbon Dioxide, CO <sub>2</sub> .....	$8.52 \times 10^{-3} + 7.4 \times 10^{-6}$	$6.52 \times 10^{-3} + 7.4 \times 10^{-6}$
Methane, CH <sub>4</sub> .....	$9.78 \times 10^{-3} + 12. \times 10^{-6}$	$7.78 \times 10^{-3} + 12. \times 10^{-6}$

TABLE 17

SPECIFIC HEATS OF GASES PER KILOGRAM.

Gases	Under Constant Pressure	Under Constant Volume
Oxygen.....	.213 + 38 × 10 <sup>-6</sup>	.150 + 38 × 10 <sup>-6</sup>
Nitrogen and Carbon Monoxide.	.243 + 42 × 10 <sup>-6</sup>	.171 + 42 × 10 <sup>-6</sup>
Hydrogen.....	3.400 + 600 × 10 <sup>-6</sup>	2.400 + 600 × 10 <sup>-6</sup>
Water Vapor.....	.447 + 324 × 10 <sup>-6</sup>	.335 + 324 × 10 <sup>-6</sup>
Carbon Dioxide.....	.193 + 168 × 10 <sup>-6</sup>	.150 + 168 × 10 <sup>-6</sup>
Methane.....	.608 + 748 × 10 <sup>-6</sup>	.491 + 748 × 10 <sup>-6</sup>

TABLE 18

MEAN SPECIFIC HEATS, BETWEEN t<sub>0</sub>° AND t<sub>1</sub>° OF GASES PER KILOGRAM.

Gases	Under Constant Pressure	Under Constant Volume
Oxygen.....	.213 + 19 × 10 <sup>-6</sup>	.150 + 19 × 10 <sup>-6</sup>
Nitrogen and Carbon Monoxide.	.243 + 21 × 10 <sup>-6</sup>	.171 + 21 × 10 <sup>-6</sup>
Hydrogen.....	3.400 + 300 × 10 <sup>-6</sup>	2.400 + 300 × 10 <sup>-6</sup>
Water Vapor.....	.447 + 162 × 10 <sup>-6</sup>	.335 + 162 × 10 <sup>-6</sup>
Carbon Dioxide.....	.193 + 84 × 10 <sup>-6</sup>	.150 + 84 × 10 <sup>-6</sup>
Methane or Marsh Gas.....	.608 + 374 × 10 <sup>-6</sup>	.491 + 374 × 10 <sup>-6</sup>

TABLE 19

VALUES OF FACTORS  $at$  AND  $(1 + at)$  FOR TEMPERATURES BETWEEN  $0^\circ$  AND  $1800^\circ$  C.

t	at	(1 + at)	t	at	(1 + at)	t	at	(1 + at)	t	at	(1 + at)
10	0.0367	1.0367	310	1.1377	2.1377	610	2.2387	3.2387	910	3.3397	4.3397
20	0.0734	1.0734	320	1.1744	2.1744	620	2.2754	3.2754	920	3.3764	4.3764
30	0.1101	1.1101	330	1.2111	2.2111	630	2.3121	3.3121	930	3.4131	4.4131
40	0.1468	1.1468	340	1.2478	2.2478	640	2.3488	3.3488	940	3.4498	4.4498
50	0.1835	1.1835	350	1.2845	2.2845	650	2.3855	3.3855	950	3.4865	4.4865
60	0.2202	1.2202	360	1.3212	2.3212	660	2.4222	3.4222	960	3.5232	4.5232
70	0.2569	1.2569	370	1.3579	2.3579	670	2.4589	3.4589	970	3.5599	4.5599
80	0.2936	1.2936	380	1.3946	2.3946	680	2.4956	3.4956	980	3.5966	4.5966
90	0.3303	1.3303	390	1.4313	2.4313	690	2.5323	3.5323	990	3.6333	4.6333
100	0.3670	1.3670	400	1.4680	2.4680	700	2.5690	3.5690	1000	3.6700	4.6700
110	0.4037	1.4037	410	1.5047	2.5047	710	2.6057	3.6057	1020	3.7434	4.7434
120	0.4404	1.4404	420	1.5414	2.5414	720	2.6424	3.6424	1040	3.8168	4.8168
130	0.4771	1.4771	430	1.5781	2.5781	730	2.6791	3.6791	1060	3.8902	4.8902
140	0.5138	1.5138	440	1.6148	2.6148	740	2.7158	3.7158	1080	3.9636	4.9636
150	0.5505	1.5505	450	1.6515	2.6515	750	2.7525	3.7525	1100	4.0370	5.0370
160	0.5872	1.5872	460	1.6882	2.6882	760	2.7892	3.7892	1120	4.1104	5.1104
170	0.6239	1.6239	470	1.7249	2.7249	770	2.8259	3.8259	1140	4.1838	5.1838
180	0.6606	1.6606	480	1.7616	2.7616	780	2.8626	3.8626	1160	4.2572	5.2572
190	0.6973	1.6973	490	1.7983	2.7983	790	2.8993	3.8993	1180	4.3306	5.3306
200	0.7340	1.7340	500	1.8350	2.8350	800	2.9360	3.9360	1200	4.4040	5.4040
210	0.7707	1.7707	510	1.8717	2.8717	810	2.9727	3.9727	1220	4.4774	5.4774
220	0.8074	1.8074	520	1.9084	2.9084	820	3.0094	4.0094	1240	4.5508	5.5508
230	0.8441	1.8441	530	1.9451	2.9451	830	3.0461	4.0461	1260	4.6242	5.6242
240	0.8808	1.8808	540	1.9818	2.9818	840	3.0828	4.0828	1280	4.6976	5.6976
250	0.9175	1.9175	550	2.0185	3.0185	850	3.1195	4.1195	1300	4.7710	5.7710
260	0.9542	1.9542	560	2.0552	3.0552	860	3.1562	4.1562	1400	5.1380	6.1380
270	0.9909	1.9909	570	2.0919	3.0919	870	3.1929	4.1929	1500	5.500	6.500
280	1.0276	2.0276	580	2.1286	3.1286	880	3.2296	4.2296	1600	5.872	6.872
290	1.0643	2.0643	590	2.1653	3.1653	890	3.2663	4.2663	1700	6.239	7.239
300	1.1010	2.1010	600	2.2020	3.2020	900	3.3030	4.3030	1800	6.606	7.606

TABLE 20

INTERNATIONAL ATOMIC WEIGHTS FOR 1905 OF THE MORE USUAL CHEMICAL ELEMENTS.

		O = 16	H = 1
Aluminum.....	Al	27.1	26.9
Antimony.....	Sb	120.2	119.3
Arsenic.....	As	75.0	74.4
Barium.....	Ba	137.4	136.4
Bismuth.....	Bi	208.5	206.9
Boron.....	B	11.0	10.9
Bromine.....	Br	79.96	79.36
Cadmium.....	Cd	112.4	111.6
Calcium.....	Ca	40.1	39.7
Carbon.....	C	12.0	11.91
Chlorine.....	Cl	35.45	35.18
Chromium.....	Cr	52.1	51.7
Cobalt.....	Co	59.0	58.55
Copper.....	Cu	63.6	63.1
Fluorine.....	F	19.0	18.9
Gold.....	Au	197.2	195.7
Hydrogen.....	H	1.008	1.000
Iodine.....	I	126.97	126.01
Iridium.....	Ir	193.0	191.6
Iron.....	Fe	55.9	55.6
Lead.....	Pb	206.9	205.35
Lithium.....	Li	7.03	6.98
Magnesium.....	Mg	24.36	24.18
Manganese.....	Mn	55.0	54.6
Mercury.....	Hg	200.0	198.6
Molybdenum.....	Mo	96.0	95.3
Nickel.....	Ni	58.7	58.3
Nitrogen.....	N	14.04	13.93
Oxygen.....	O	16.00	15.88
Phosphorus.....	P	31.0	30.77
Platinum.....	Pt	194.8	193.3
Potassium.....	K	39.15	38.85
Silicon.....	Si	28.4	28.2
Silver.....	Ag	107.93	107.11
Sodium.....	Na	23.05	22.88
Strontium.....	Sr	87.6	86.94
Sulphur.....	S	32.06	31.82
Tin.....	Sn	119.0	118.1
Titanium.....	Ti	48.1	47.7
Tungsten.....	W	184.0	182.6
Uranium.....	U	238.5	236.7
Vanadium.....	V	51.2	50.8
Zinc.....	Zn	65.4	64.9

TABLE 21

*Conversion Tables*<sup>1</sup>.

## CONVERSION OF TEMPERATURE SCALES.

Fahrenheit = F

Centigrade = C

Absolute = A

$$F = \frac{9}{5} C + 32$$

$$F = \frac{9(A - 273)}{5} + 32$$

$$C = \frac{5(F - 32)}{9}$$

$$C = A - 273$$

$$A = \frac{5(F - 32)}{9} + 273$$

$$A = C + 273$$

One large calory = 3.968 32 B. t. u. Log. 0.598 6067.

One B. t. u. = 0.251 995 8; large calory 1.401 3933.

One inch = 2.54 centimeters; log. 0.404 8346.

One foot = 30.480 centimeters; log. 1.484 0158.

One centimeter = 0.393 700 inch; log. 1.595 1654.

One square inch = 6.451 6 square centimeters; log. 0.809 6692.

One square foot = 929.034 square centimeters; log. 2.968 0317.

One square centimeter = 0.155 000 square inch; log. 1.1903308.

One square centimeter = 0.001 076 387 square foot; log. 3.031 9683

One cubic inch = 16.387 16 cubic centimeters; log. 1.214 5038.

One cubic foot = 28 317.0 cubic centimeters; log. 4.452 0475.

One cubic centimeter = 0.061 023 4 cubic inches; log. 2.7854 962.

<sup>1</sup> Carl Herig, "Conversion Tables."

One cubic meter = 61 023.4 cubic inches; log. 4.785 4962.

One cubic meter = 35.314 5 cubic feet; log. 1.547 9525.

One kilogram = 2.204 62 pounds (av.); log. 0.343 3342.

One pound (av.) = 0.453 593 4 kilogram; log. 1.656 6658.

*Pressures in Terms of Water, Mercury, Atmosphere :*

1 kilogram per sq. mm.	= 100 kg. per sq. cm.	
	= 1422.34 lb. per sq. in.	3.153 0034

1 kilo per sq. cm.	= 2048.17 lb. per sq. ft.	3.311 3659
	= 32.8083 ft. of water	1.515 9842
	= 28.9572 in. of mercury	1.461 7564
	= 735.514 mm. of mercury	2.866 5910
	= .967782 atmosphere	1.985 7774

1 atmosphere	= 2116.35 lb. per sq. ft.	3.325 5885
	= 760. mm. of mercury	2.880 8136
	= 33.9006 ft. of water	1.530 2068
	= 14.6969 lb. per sq. in.	1.167 2260
	= 1.03329 kg. per sq. cm.	.014 2226

1 pound per square inch	= 703.067 kg. per sq. m.	2.846 9966
	= 51.7116 mm. of mercury	1.713 5876
	= 2.306 65 ft. of water	.362 9808
	= 2.035 88 in. of mercury	.308 7530
	= .070 306 7 kg. per sq. cm.	2.846 9966
	= .0680415 atmosphere	2.832 7740

1 inch of mercury column	= 70.7310 lb. per sq. ft.	1.849 6095
	= 25.40005 mm. of mercury	1.404 8346
	= 1.13299 ft. of water	0.054 2278
	= .491187 lb. per sq. in.	1.691 2470
	= .0345337 kg. per sq. cm.	2.538 2436
	= .0334211 atmosphere	2.524 0210



1 foot of water column	= 304.801 kg. per sq. m.	2.484 0158
	= 62.4283 lb. per sq. ft.	1.795 3817
	= 22.4185 mm. of mercury	1.350 6068
	= .43353 lb. per sq. in.	1.637 0192
	= .0304801 kg. per sq. cm.	2.484 0158
	= .029498 atmosphere	2.469 7932
1 meter of water column	= 204.817 lb. per sq. ft.	2.311 3659
	= 73.5514 mm. of mercury	1.866 5910
	= 3.28083 ft. of water	.515 9842
	= 2.89572 in. of mercury	.461 7564
	= 1.42234 lb. per sq. in.	.153 0034
	= .1 kg. per sq. cm.	1.000 0000
	= .0967782 atmosphere	2.985 7774
1 mm. of mercury column	= 13.59593 kg. per sq. m.	1.133 4090
	= 2.78468 lb. per sq. ft.	.444 7749
	= .044606 ft. of water	2.649 3932
	= .03937 in. of mercury	2.595 1654
	= .019338 lb. per sq. in.	2.286 4124
	= .01359593 meter of water	2.133 4090
	= .00135959 kg. per sq. cm.	3.133 4090
	= .00131579 atmosphere	3.119 1864
1 inch of water column	= 25.4001 kg. per sq. m.	1.404 8346
	= 5.20236 lb. per sq. ft.	.716 2005
	= 1.8682 mm. of mercury	.271 4256
	= .073552 in. of mercury	2.866 5910
	= .036128 lb. per sq. in.	2.557 8380
	= .0254001 m. of water	2.404 8346
	= .00254001 kg. per sq. cm.	3.404 8346
	= .0024582 atmosphere	3.390 6120

*Linear Velocities.*

One meter per second	= 3.280583 feet per second	0.515 9842
One foot per second	= .304801 meter per second	1.484 0158

TABLE 22  
ELEMENTARY ANALYSES AND CALORIFIC POWERS OF FUELS. I

No.	FUELS	ELEMENTARY ANALYSIS.										ELEMENTARY ANALYSIS, ASH AND MOISTURE-FREE BASIS				Experimental Calorific Power	Exp. Calorific Power on Ash and Moisture-free Basis = $Q_0$	Calorific Power Calculated from Mabier Formula $Q_0 = \frac{H34500 + C8140 - 3000(O + N)}{100}$	Remarks							
		Carbon			Hydrogen			Oxygen and Nitrogen			Ash			Carbon						Hydrogen			Oxygen and Nitrogen			
		%	%	%	%	%	%	%	%	%	%	%	%	%	%					%	%	%	%	%	%	%
1	Pennsylvania Anthracite	86.456	1.995	2.199	3.450	5.900	95.373	2.201	2.426	7844	8256	8450														
2	Anthracite from La Mure (Isere)	86.564	1.367	2.969	4.700	4.000	95.241	1.504	3.255	7466	8216	8152														
3	Anthracite from Hay-Duong (Tonking)	86.114	2.000	4.626	3.260	4.000	92.855	2.157	4.988	7533	8121	8172														
4	Kebao Anthracite Coal	85.744	2.733	2.731	2.800	5.450	93.456	3.065	3.479	7928	8432	8531										0.70% S				
5	Commentary Anthracite Coal	84.928	2.892	5.003	1.775	5.400	91.483	3.115	5.382	7850	8456	8260										0.79% S				
6	Blansy Anthracite Coal	82.746	2.916	6.278	1.760	6.300	90.000	3.172	6.828	7773	8206	8215														
7	Grande Combe Anthracite Coal	84.068	3.631	4.220	0.831	7.250	91.459	3.930	8.591	7850	8540	8670														
8	Creusot Anthracite Coal	89.386	3.661	3.703	1.800	1.450	92.389	3.784	3.827	8404	8987	8712														
9	Anzin, St. Marc Shaft	88.473	4.139	4.338	1.350	1.700	91.256	4.269	4.475	8392	8656	8767										0.673% S				
10	Grande Combe, St. Jean Shaft	87.164	4.265	4.161	0.610	3.800	91.185	4.462	4.353	8371	8756	8632										3.10% Ash collected in calorimeter				
11	La Roche-la-Molliere	85.691	4.167	5.242	0.900	4.000	90.106	4.382	5.612	8417	8767	8681										0.810% S				
12	Aniche, Ferdinand Seam	85.934	4.198	5.240	0.625	4.000	90.104	4.402	5.494	8426	8634	8688										0.866% S				
13	Anzin, Thick Seam, Encles Shaft	83.754	4.385	5.761	1.100	5.000	89.195	4.670	6.135	8051	8574	8689										0.566% S				
14	Ronchamp, 2d Seam, Magny Shaft	79.200	4.311	5.689	1.200	9.700	88.989	4.838	6.273	7839	8787	8717										0.868% S				
15	Lens, 1st 90 Seam, No. 8 Shaft	87.736	4.678	5.036	1.000	1.550	90.032	4.800	5.168	8614	8829	8839														
16	Carmaux	85.200	4.724	7.076	1.500	1.500	87.835	4.870	7.295	8380	8639	8611														
17	St. Etienne, 8th Seam	85.638	4.628	5.366	1.350	3.000	89.530	4.838	5.632	8482	8867	8768														
18	St. Etienne, 6th Seam	81.546	4.772	5.432	1.250	4.000	89.231	5.028	5.743	8392	8657	8629										0.591% S				
19	Porta (Gard)	78.240	4.370	7.700	0.780	8.910	86.520	4.840	8.040	7046	8667	8452														



TABLE 23

PERCENT. TABLE OF STACK MEASUREMENTS FOR REGENERATIVE FURNACES.

HOURLY CON-SUMPTION OF	INNER WIDTH AT TOP	INNER WIDTH AT BASE	THICK-NESS OF WALLS AT	Height of Stack	Stack of Square Section		Stack of Circular Section		Mean Diameter, $D$		Mean Section $P$		Volume of Enclosed Gas Column		Weight of the		$P-P_1$		$V = \sqrt{2gh}$ THEORETICAL	REAL $V$	$F \frac{V}{3}$	$\frac{1}{6} F \frac{V}{3}$
					Stack of Square Section	Stack of Circular Section	Base	Top	Gas Column at 250° C.	Air Column at 0° C.	$Kg.$	$Kg.$	$Kg.$	$Kg.$	Velocity	Velocity	$h = \frac{P-P_1}{1.293 F}$	$m^3$ per Sec.	Resistance Due to Pipes	Resistance Due to Fines	$m^3$ per Sec.	Resistance Due to Fines
Coal	10	10	33	18	0.24	0.27	0.36	0.40	0.32	0.33	0.33	0.34	0.09	0.09	0.34	0.34	3.4	0.245	0.041	0.041	0.245	0.041
Wood	20	20	38	18	0.32	0.36	0.48	0.54	0.45	0.48	0.48	0.48	0.16	0.16	0.45	0.45	6.8	0.592	0.10	0.10	0.592	0.10
	30	30	41	18	0.38	0.43	0.56	0.63	0.53	0.56	0.56	0.56	0.22	0.22	0.53	0.53	8.15	0.890	0.143	0.143	0.890	0.143
	40	40	44	18	0.47	0.53	0.67	0.72	0.66	0.67	0.67	0.67	0.28	0.28	0.66	0.66	8.15	1.180	0.197	0.197	1.180	0.197
	50	50	45	18	0.55	0.62	0.78	0.80	0.77	0.77	0.77	0.77	0.34	0.34	0.77	0.77	8.15	1.480	0.247	0.247	1.480	0.247
	75	75	48	18	0.73	0.83	1.00	1.01	0.88	0.88	0.88	0.88	0.47	0.47	0.88	0.88	10.70	2.13	0.352	0.352	2.13	0.352
	100	100	51	18	0.83	0.93	1.10	1.11	0.98	0.98	0.98	0.98	0.55	0.55	1.00	1.00	12.60	2.86	0.477	0.477	2.86	0.477
	150	150	57	18	1.01	1.13	1.30	1.31	1.16	1.16	1.16	1.16	0.66	0.66	1.16	1.16	14.60	4.45	0.741	0.741	4.45	0.741
	200	200	60	18	1.16	1.30	1.47	1.48	1.29	1.29	1.29	1.29	0.77	0.77	1.29	1.29	16.50	6.97	0.995	0.995	6.97	0.995
	250	250	63	18	1.30	1.47	1.66	1.67	1.49	1.49	1.49	1.49	0.88	0.88	1.49	1.49	18.40	8.45	1.233	1.233	8.45	1.233
	300	300	65	18	1.47	1.66	1.83	1.84	1.68	1.68	1.68	1.68	1.00	1.00	1.68	1.68	20.30	10.44	1.447	1.447	10.44	1.447
	350	350	66	18	1.66	1.83	2.00	2.01	1.82	1.82	1.82	1.82	1.11	1.11	1.82	1.82	22.20	12.33	1.660	1.660	12.33	1.660
	400	400	69	18	1.83	2.00	2.17	2.18	1.97	1.97	1.97	1.97	1.23	1.23	2.00	2.00	24.10	14.30	1.927	1.927	14.30	1.927
	450	450	69	18	2.00	2.17	2.34	2.35	2.13	2.13	2.13	2.13	1.34	1.34	2.13	2.13	26.00	16.10	2.233	2.233	16.10	2.233
	500	500	71	18	2.17	2.34	2.51	2.52	2.30	2.30	2.30	2.30	1.45	1.45	2.30	2.30	27.90	18.00	2.477	2.477	18.00	2.477
	550	550	71	18	2.34	2.51	2.68	2.69	2.46	2.46	2.46	2.46	1.56	1.56	2.46	2.46	29.80	19.90	2.772	2.772	19.90	2.772
	600	600	74	18	2.51	2.68	2.85	2.86	2.63	2.63	2.63	2.63	1.67	1.67	2.63	2.63	31.70	21.80	3.067	3.067	21.80	3.067
	700	700	74	18	2.68	2.85	3.02	3.03	2.80	2.80	2.80	2.80	1.78	1.78	2.80	2.80	33.60	23.70	3.362	3.362	23.70	3.362
	800	800	77	18	2.85	3.02	3.19	3.20	3.00	3.00	3.00	3.00	1.89	1.89	3.00	3.00	35.50	25.60	3.657	3.657	25.60	3.657
	900	900	77	18	3.02	3.19	3.36	3.37	3.13	3.13	3.13	3.13	2.00	2.00	3.13	3.13	37.40	27.50	3.952	3.952	27.50	3.952
	1000	1000	77	18	3.19	3.36	3.53	3.54	3.30	3.30	3.30	3.30	2.11	2.11	3.30	3.30	39.30	29.60	4.247	4.247	29.60	4.247
	1100	1100	77	18	3.36	3.53	3.70	3.71	3.46	3.46	3.46	3.46	2.22	2.22	3.46	3.46	41.20	31.70	4.542	4.542	31.70	4.542
	1200	1200	77	18	3.53	3.70	3.87	3.88	3.63	3.63	3.63	3.63	2.33	2.33	3.63	3.63	43.10	33.80	4.837	4.837	33.80	4.837
	1300	1300	79	18	3.70	3.87	4.04	4.05	3.79	3.79	3.79	3.79	2.44	2.44	3.79	3.79	45.00	35.90	5.132	5.132	35.90	5.132
	1400	1400	79	18	3.87	4.04	4.21	4.22	3.96	3.96	3.96	3.96	2.55	2.55	3.96	3.96	46.90	38.00	5.427	5.427	38.00	5.427
	1500	1500	79	18	4.04	4.21	4.38	4.39	4.13	4.13	4.13	4.13	2.66	2.66	4.13	4.13	48.80	40.10	5.722	5.722	40.10	5.722

TABLE 24

Coefficients of heat conductivity in calories (sq. m.-hour-°C. <sup>1</sup>):

Masonry.....	1.3 to 2.1
Firebrick.....	.7
Air.....	.0175 to .0205
Cement.....	.059
Water.....	.44 to .56
Iron.....	40.00 to 70.00
Copper.....	330.00

<sup>1</sup> Lanboldt & Boernstein, "Phys.-Chem. Tabellen." Also "Ingenieurs Taschenbuch."  
Vol. II, pp. 408-411.

## BIBLIOGRAPHY.

---

### FUELS AND CALORIMETRY.

Metallurgy, Vol. I. Refractory Materials and Fuel. John Percy, M.D.

Fuel and its Applications. E. J. Mills, D. Sc., and E. J. Rowan, C. E.

Fuel—Its Combustion and Economy. C. W. Williams, A. I. C. E., and D. K. Clark.

Fuel. R. Galloway, F. C. S.

Fuel and Water. F. Schwakhöfer and W. R. Browne, M. A.

Introduction to the Study of Metallurgy. W. C. Roberts-Austen, F. R. S.

Fuel and its Efficiency. B. H. Thwaite, J. I. S. I. 1892, Vol. I.

Geology of Coal. Chemistry of Coal. Coal. Edited by T. E. Thorpe.

Coal. T. H. Huxley, F. R. S.

Sulphur in Coal. G. H. Bailey, J. S. C. I. 1889.

Briquette Fuel. W. Colquhoun, P. I. C. E. Vol. CXVIII.

Heating Power of Coal. W. Thomson, F. C. S. J. S. C. I. 1889.

Fuel Purification. P. Bateson, J. S. C. I. 1891.

Liquid Fuel for Mechanical and Industrial Purposes. E. A. Brayley Hodgetts.

Liquid Fuel. L. T. Wright, J. S. C. I. 1887.

Liquid Fuel. G. Stockfleth, J. S. C. I. 1894.

Liquid Fuel. H. Aydon, P. I. C. E., Vol. LII.

Natural Gas. F. C. Phillips, J. S. C. I. 1894.

Gaseous Fuel. Sir E. Lowthian Bell, J. I. S. I., 1889, Vol. II.

Fuel Gas. B. Loomis, J. I. S. I., Vol. II.

- Use of Gas as a Heating Agent compared with Solid Fuel. G. E. Davis, J. S. C. I. 1883.
- Generation and Application of Gas. A. Wilson, J. S. C. I. 1883.
- Gaseous Fuel. L. T. Wright, J. S. C. I. 1883.
- Dowson Gas. J. S. C. I. 1888.
- Water Gas. J. F. Bell, J. S. C. I. 1889.
- Fuel Value of Gases. H. L. Payne, J. S. C. I. 1893.
- Gasification of Coal and Oil. P. Dvorkovitch, J. S. C. I. 1893.
- Gaseous Fuel. G. Ritchie, J. W. of S. I. S. I. Vol. I.
- Note on the Efficiency of Gaseous Fuels. F. A. Matthewman, J. W. of S. I. S. I.; Vol. I.
- Sacrifice of Heat in Making Producer-Gas. J. Ormiston, J. W. of S. I. S. I. Vol. I.
- Notes on Water Gas. G. Ritchie, J. W. of S. I. S. I., Vol. II.
- On Gas Producers. H. J. Bowman, P. I. C. E., Vol. LXXXIV.
- Efficiencies of Gas Producers. C. F. Jenkin, P. I. C. E., Vol. CXXIII.
- Mond Producer-Gas. J. H. Darby, J. I. S. I. 1896, Vol. I.
- Notes on Fuel. B. H. Thwaite, J. I. S. I. 1892, Vol. I.
- Manuel pour l'Essai des Combustibles et le Contrôle des Appareils de Chauffage. F. Fischer.
- Analyse Chimique et Essai des Combustibles. L. Campredon.
- Tableaux des Essais de Combustibles Minéraux. Ad. Carnot.
- Conférence sur le Pouvoir Calorifique des Combustibles et l'Appareil de M. Mahler. E. Goutal.
- Les Matières Volatiles et le Pouvoir Calorifique des Houilles. E. Goutal.
- Étude sur la Fusibilité des Cendres de Combustibles. Le Chatelier et Chantepie.
- Contribution à l'Étude des Combustibles. P. Mahler.
- Études sur les Combustibles, Solides, Liquides et Gazeux. P. Mahler.
- Les Combustibles, Solides, Liquides et Gazeux. D. H. J. Phillips.
- Pouvoir Calorifique des Combustibles, Solides, Liquides et Gazeux. Scheurer-Kestner.
- Essai des Combustibles. D. Siderski.
- Fuels and Refractory Materials. A. Humboldt Sexton.

- Die Untersuchung und Bewerthung der Brennstoffe. P. Fritzsche.  
 Das gas als Leucht-, Heiz-, und Kraftstoff. O. Pfeiffer.  
 Heizwert der Kohlen Osterreich-Ungarns und Preussisch-Schle-  
 siens. Schwackhöfer.  
 Chemische Technologie des Brennstoffe. F. Fisher.  
 Ueber die Bestimmung der Nutzbaren Verbrennungswärme.  
 Dr. K. Kroeker.  
 Chemische und Calorimeterische Untersuchung von Brennstoffen.  
 Dr. H. Longbein.  
 Die Bestimmung des Heizwerthen von Brennmaterialen. H. von  
 Jüptner.  
 Metallurgical Laboratory Notes. H. M. Howe.  
 Ready Reference Tables. Carl Hering.  
 New Form of Calorimeter. W. Thomson, J. S. C. I. 1886.  
 Traité Pratique de Calorimétrie Chimique. M. Berthelot.  
 Das Parische Calorimeter. Dr. G. Lunge.

#### COMBUSTION.

- Flame. L. T. Wright, J. S. C. I. 1887.  
 Flame. F. J. Rowan, J. S. C. I. 1889.  
 Flame. A. Smithells, J. C. S. 1892.  
 Combustion. F. Siemens, J. I. S. I. 1886, Vol. II.  
 Combustion of Coal in House Fires. J. B. Cohen, D. Sc., and  
 G. Hefford, J. S. C. I. 1893.  
 Luminosity of Flame. Profs. Lewes and Smithells, J. C. S. and  
 J. S. C. I. 1892 *et sequa*.  
 Combustion of Powdered Fuel. J. R. Crampton, J. I. S. I. 1873.  
 Die Lehre von den Brennmaterialen. R. Krüger.  
 Die Gasfeuerungen. A. Ledebur.  
 Die Feuerungen mit flüssigen Brennmaterialen. J. Lew.

#### GAS ANALYSIS.

- Volumetric Analysis. Francis Sutton, F. I. C., F. C. S. 1896.  
 The Chemical Analysis of Iron. Andrew Alexander Blair. 1902.  
 Traité d'Analyse des Substances Minérales. Adolphe Carnot.  
 Ausgewählte Methoden des Analytischen Chemie. A. Classen.



- Quantitative Analysis. J. C. Olsen.  
Analyse des Gas. Pozzi-Escot.  
Method of Gas Analysis. W. Hempel. Translated by L. M. Dennie.  
Techno-Chemical Analysis. G. Lunge. Translated by A. T. Cohn.  
Analytical Chemistry. F. P. Treadwell, Ph. D. Translated by Wm. T. Hall, S. B.  
The Gases of the Atmosphere. Wm. Ramsay.

## THERMAL CHEMISTRY.

- Application of Thermal Chemistry to Metallurgical Problems.  
A. Pourcel, J. I. S. I. 1889, Vol. I.  
Thermal Chemistry. M. Pattison Muir and M. Wilson.  
Technische-thermochemische Berechnungen zur Heizung. A. Naumann.  
Lehr und Handbuch der Thermochemie. A. Naumann.  
Thermo-dynamics and Chemistry. Duhem-Burgess.

## CHIMNEYS.

- Boiler Chimneys. R. Wilson Crosby.  
Mechanical Engineers' Pocket Book. W. Kent.  
Trans. A. S. M. E., Vol. XI. De Volsón Wood.  
Steam Engines. Prof. Rankine.  
Treatise on Heat. Thomas Box.  
Trans. A. S. M. E. Vol. XI. R. H. Thurston.  
Anlage und Betrieb der Dampfkessel. Reiche.  
Encyklopädie. Prechtl's.

## PYROMETRY.

- Heisch & Folkard's Pyrometer. F. Hurter, J. S. C. I. 1886.  
Le Chatelier's Pyrometer. W. C. Roberts-Austen, F. R. S., J. I. S. I. 1891, Vol. I.  
Autographically Recording Pyrometer. W. C. Roberts-Austen. J. I. S. I. 1892, Vol. I.

Recording Pyrometers. W. C. Roberts-Austen, J. I. S. I. 1893, Vol. I.

Platinum Pyrometers. H. L. Callendar, J. I. S. I. 1892, Vol. I.

A New Optical Pyrometer. B. H. Thwaite, J. I. S. I. 1892, Vol. I.

High Temperature Measurements. Le Chatelier-Boudouard-Burgess.

Iron and Steel Institute. 1904.

#### FURNACES.

Coke Ovens. A. B. Cochrane. Pr. Inst. Mech. Eng. 1801.

New Form of Siemens Furnace. J. Head and M. P. Pouff, J. I. S. I. 1889, Vol. II.

Regenerating Heat in the New Form of Siemens Furnace. R. Ackerman, J. I. S. I. 1890, Vol. I.

Improved Design for Open-hearth Steel Furnaces. B. H. Thwaite, P. S. S. I., Vol. VI.

Calorific Power of Puddling Furnace. J. Cubillo, J. I. S. I. 1892, Vol. I.

Efficiency of Reverberatory Furnaces. J. Cubillo, P. S. S. I., Vol. VI.

Die Oefen für Metallurgische Processe. A. Ledebur.

Chemische-calorische Studien über Generatorem und Martin-Oefen. Toldt.

Allgemeine Anweisung für den Bau und den Betrieb der Regenerativ-Gasöfen. R. Schneider.

Regenerativ-Gasöfen. F. Toldt.

Travail des Metaux dérivés du Fer. L. Gages.

Metallurgical Calculations. Electro-Chemical and Metallurgical Industry, Vol. III. J. W. Richards.

Le Chauffage Industriel et les Fours à Gaz. Emilio Damour.

#### METALLURGY.

Iron, Steel and Other Alloys. Henry M. Howe.

Manufacture and Properties of Iron and Steel. Harry Huse Campbell.

- Metallurgy of Steel. F. W. Harboard, Assoc. R. S. M., F. I. C.  
The Metallurgy of Steel. H. M. Howe.  
The Metallurgy of Lead. H. O. Hofman.  
Modern Copper Smelting. Edward Dyer Peters, Jr.  
The Metallurgy of Zinc. Walter Renton Ingalls.  
Introduction to the Study of Metallurgy. Sir W. C. Roberts-  
Austen.  
Die Anlage und der Betrieb der Eisenhütten. E. F. Dürre.  
Das Eisenhüttenwesen Schwedens. J. V. Ehrenwerth.  
Abhandlungen über Metallurgie (deutsch von Kupelweiser).  
M. L. Gruner.  
Des Ingenieurs Taschenbuch. Hütte (Verein).  
Handbuch der Eisenhüttenkunde. A. Ledebur.  
Ausführliches Handbuch der Eisenhüttenkunde. H. Wedding.  
Traité de Métallurgie Générale. G. Schnabel.  
Métallurgie de Zinc. A. Lodin.  
Traité Théorique et Pratique de Métallurgie Générale. L. Babu.  
Métallurgie. Urbain Le Verrier.  
Aluminum. Dr. J. W. Richards.



# INDEX.

A			
	PAGE		PAGE
"Ados" automatic gas analyzer, section of.....	187	Berthelot.....	7, 10
Air, atmospheric, in a furnace,		Berthelot-Mahler apparatus	196
value of.....	59	ready for operation...	197
leaks, when of importance.	136	calorimeter.....	197
necessary to have excess of		Bibliography.....	300-5
in a direct-fired furnace.	71	Bicheroux furnace.....	37, 73, 76
pre-heating of.....	49	Bied, J., cited.....	256
primary.....	40	Biedermann.....	46, 95, 116
primary effect of pre-heating.....	122	Blacksmith's forge as a type of	
primary, secondary, and		furnace.....	75
gas, diagram showing		Block, perforated, section of..	254
theoretical economies		Boëtius furnace.....	72, 73, 76
from the pre-heating		Boiler, steam.....	1
of.....	126	steam, practice—field for	
ratio of primary to secondary,		improvement in.....	84
modified by		Boilers, for torpedo-boats, data	
steam.....	63	concerning.....	83
regenerator.....	251	(marine) multitubular,	
secondary.....	41	consideration of.....	78
secondary, furnaces that		multitubular, heat lost and	
recuperate by means of.	86	utilized in.....	84
total, advantage of recuperation by.....	110	steam, follow furnaces....	76
total, pre-heating of.....	108	steam; heat lost when	
volume of injected in the		combustion is effected	
chambers.....	137	by large excess of air..	78
Asphaltum, action of in gas-producer.....	65	Boiling points, apparatus for	
Atwater calorimeter modifications.....	193	the determination of... ..	157
		Bomb calorimeter.....	193, 194
		calorimeter, calculation of	
		results from use of....	202
		Breslau, cited.....	246
		Bromine water.....	180
		Buire-Lencauchez producers...	64
		Bunte burette.....	179
B		C	
Bardolle, L.....	46	Calories, hypothetical perfect	
Barus.....	156	exchange of between	
Batho furnace.....	242	hot and cold gases.....	142
Belleville boiler.....	78, 82	lost and utilized in furnaces	
boiler and economizer, section through.....	79, 80	fired with Siemens gas,	
Belleville, M.....	79	double recuperation....	95

	PAGE		PAGE
Calories lost and utilized in furnaces fired with Siemens gas, single recuperation..	90	Chloride, cuprous solution.....	180
Calorific power defined.....	10	Coal, bituminous, temperature of combustion of.....	22
power under constant pressure.....	10	hydrocarbons of, action of in gas-producer.....	65
Calorimeter test, calculation of.	203	powdered, method of using.	274
Calorimeters.....	193	ultimate analysis and calorific power of.....	131
Calorimetric corrections.....	208, 209	Coal-dust, explosion of.....	273
method of Berthelot.....	129	proper care of.....	273
tests, accuracy obtainable in.....	205	stokers.....	275
Calorimetry.....	192	Coke oven.....	265, 267
Calory, large, used in this book.	7	Combustion, books on.....	302
Campbell 50-ton basic furnace.....	106, 107, 109	calculations.....	235, 236, 237
H. H., cited.....	246, 266	complete, in boilers, without excess of air, desideratum.....	85
Cane, pyrometric, for protecting wires of Le Chatelier thermo-electric pyrometer.....	152	general equation of the temperature of.....	14
pyrometric, use of in tests.	135	graphic method for determining the temperatures of (diagram).....	15
Carbon dioxide, action of in gas-producer.....	65	heat of.....	10
dioxide, dissociation of...	34	phenomena, scientific data necessary for the study of.....	7
dioxide, effect of in gas-producer.....	116	principles relating to.....	58
dioxide, injection into gas-producers of pure hot..	117	products at 1500°, calories contained in.....	138
dioxide, proposed injection of in gas-producers.....	116	products, so-called regenerated.....	51
dioxide, ratio of the volume of to that of nitrogen	59	products, method of ascertaining.....	22
hydrogen and ash, determination of.....	223	products, thermal capacities for the volumes of.....	19
monoxide.....	186	products, volumetric analysis of.....	134
monoxide, dissociation of.	35, 36	reactions of.....	97, 116
monoxide, temperature of combustion of.....	19	in recuperative gas-fired furnaces, hypotheses required for theory of....	67, 68
temperature of combustion of.....	17, 21	specific heats of.....	205
Case, W. L.....	46	temperatures of, defined..	14
Cement industry, points concerning.....	275	temperature of, how computed.....	14
Ceramic furnaces.....	73	Commission du Grisou.....	7, 14
Checkerwork, calculation concerning.....	248	Compagnie Parisienne du Gaz.	87, 92, 99
Chemistry, thermal, books on.	303	Parisienne du Gaz, retort gas furnaces of.....	86
Chimney (of gas furnace), office and limits of.....	41	Coquillon platinum spiral.....	186
Chimneys.....	231	Couple, Le Chatelier thermo-electric.....	171
books on.....	303		
required height of, by calculation.....	231-233		

	PAGE		PAGE
Couple, standardization of, method of accomplishing.....	155, 156	Firing, direct, type of furnaces using.....	77
Couples, some types of.....	149	Fisher-Gautier.....	46, 47
Currents, gaseous, minimum times of sojourn of in regenerative furnaces....	241	Fletcher furnace.....	159
Cylindrical tube, section through, equivalent to half of the perforated block.....	255	Flue connections, incorrect, for a horizontal regenerative chamber.....	243
D		connections, incorrect, for a vertical regenerative chamber.....	244
Dampers, importance of in furnaces.....	43	design, correct, for a hor- izontal regenerative chamber.....	244
Day.....	150	Focusing device of the Féry heat-radiation pyrome- ter, mirror type.....	172
Dellwick.....	45	Freezing point of metal, appar- atus for determining....	160
Dellwick-Fleisher water-gas producer.....	61	Fuel, calorific power of, ap- proximate determina- tion by Mahler and Gou- tal formulas.....	220
Dowson.....	46	character of to be considered in making calculations.....	143
Draught, improvement of in gas-producers.....	46	combustion, air required in (table).....	9
Drehschmidt tube.....	186, 188	economy.....	1, 2
Duff gas-producer.....	64	elementary analysis of....	223
Dulong formula for heating effect of coal.....	192	gaseous, use of in boilers not recommended.....	84
Dust-coal firing, adaptation of.	273	powdered, application of to furnace firing.....	275
E		powdered, list of U. S. patents covering the stoking of.....	283-286
Ebelmen fusion producer....	43	powdered, preparation of.	272
gas-producer.....	45	Fuels and calorimetry, books on.....	300-302
producer.....	94, 110	apparatus for elementary analysis of.....	224
Ecole Nationale des Mines....	14	Furnace, best, points concerning calculation of the effi- ciency of a.....	69, 136
Edison Portland Cement Co., furnace of.....	274	determination of the effi- ciency of a.....	56
Efficiency, recuperative, de- fined.....	56	dimensions.....	3
Elliott apparatus for gas an- alysis.....	178, 179	direct-fired, diagram show- ing percentage of heat utilized and lost.....	75
apparatus fitted with Drehschmidt platinum tube for determination of hydrogen and me- thane.....	185	direct-fired, elements of the value of.....	73
E. m. f., necessity of vari- ability of in couples....	150	with double recuperation, heat balance-sheet of..	93
F			
Ferraris zinc gas furnace.....	274		
Firebrick blocks, perforated, for the parallel counter- current system of heat recuperation.....	258		

	PAGE		PAGE
Furnace, electric-resistance, ad-		Furnaces, condensed classifica-	
vantages of.....	159	tion of various types....	123
gas, description of parts...	40	direct-fired, characteristics	
gas-fired, some advantages		of.....	71
of.....	39	direct-fired, heat losses for	
gas, industries employed		all temperatures....73, 74,	75
in.....	38	direct-fired, limit of tem-	
gas, reasons for its success.	39	peratures of.....	17
glass.....	1	direct-fired, principal in-	
glass, Gobbé system.....	94	dustrial applications of.	71
glass-pot, defects of.....	39	with double recuperation	
glass tank, fired with Sie-		for secondary air and	
mens gas.....	92	gas.....	92
glass, typical example of		efficiencies of when fired	
supplementary recuper-		with gas obtained from	
ation.....	115	producers injected with	
Hoffman.....	1	part of the products of	
horseshoe, disposition of		combustion.....	119
parts in.....	49	electric.....	161
horseshoe, movement of		electric, suited to pyro-	
flame in.....	50	metric work.....	161
how to determine the value		gas, improvements in....	43
of a.....	129	followed by steam boilers.	76
illuminating-gas muffle, of		gas, classification of.....	37
Compagnie Parisienne		gas, description and func-	
du Gaz.....	89	tions of essential pa ts..	40
new Siemens.....48-51, 121,	187	gas, origin and develop-	
parts, improvements in...	39	ment of.....	37
proper (in gas furnace),		gas-fired, different applica-	
limits of.....	41	tions of.....	3
puddling.....	1	gas-fired, when economi-	
puddling, calculation of		cally substituted.....	128
lost heat in.....	76	gas-fired reverberatory, ra-	
puddling, of the forges		diation in.....	50
d'Eurville.....	77	gas-fired, second group of	
puddling, with water-		gas-fired, twelve systems	
cooled hearth.....	77	considered.....	53
Queneau electric resistance		glass, heat utilization in..	76
crucible.....	162	heat balance-sheets of....	129
re-heating.....	1	large, with long flames....	3
rotary clinkering, for mak-		making use of regeneration	
ing Portland cement—		of combustion products.	116
efficiency test of....277-282		medium recuperative, prog-	
selection of proper type..	1	ress to be sought here.	95
study of the heat efficiency		without recuperation....	73
of a.....	129	medium temperature, best.	123
triple recuperation, special		with one or two pairs of	
interest of.....	122	chambers, difference of	
Furnaces (see also under Gas).		efficiency in.....	123
books on.....	304	proper and improper meth-	
ceramic.....	73	ods of estimating value	
classified.....	141	of.....	143
comparative table of all		proper, recent modifica-	
systems.....124, 125		tions in.....	49



	PAGE		PAGE
Furnaces that recuperate by secondary air alone...	86	Gas firing, with recupera-	2
small, with short flames...	3	tion.....	
for temperatures of about 1000°, classification of...	128	furnace, description of parts.....	40
with triple recuperation, high efficiency of.....	114	furnace, industries employed in.....	38
what type is superior theoretically.....	144	furnace, reasons for its success.....	39
		furnace, recuperative illuminating.....	239
G		furnaces, classification of.....	37
Galvanometer of Cambridge Scientific Instrument Co.	148	furnaces, description and functions of essential parts.....	40
Cambridge Scientific Instrument Co. direct-reading, for the Féry heat-radiation pyrometer	173	furnaces, improvements in.....	43
d'Arsonval.....	171	furnaces, origin and development of.....	37
operation of.....	167	furnaces, retort, Lencau-	86
Pellin registering.....	148, 166	chez system.....	
where to place for tests..	155	furnaces, retort, Siemens system.....	86
of Siemens and Halske..	148	masses, reacting only here considered.....	66
Siemens-Halske recording..	167	mixed, advantages of in recuperation.....	46
Galvanometers, pyrometric...	166	mixed, in case of recuperation by total air.....	110
types of.....	148	mixed, defined.....	51
Gas (see also under FURNACES).		mixed, higher efficiency of due to better recuperation.....	108
analysis.....	133, 175	mixed, how obtained....	46
analysis, calculations in	189	mixed, for single recuperation, slight advantage of.....	101
-analyzing machine, automatic self-registering...	191	mixed, tendency to use... (natural, Iola, Kan.), analysis of and calculations based on.....	28-33
analysis, books on.....	302-303	natural, not capable of efficient pre-heating....	65
and air ports, types of....	268	(natural, Pittsburg), combustion temperatures of.....	25
and air flues leading to regenerator, minimum section of.....	250	(natural, Pittsburg), data concerning combustion of.....	26, 27, 28
calorific power of.....	219	(natural, Pittsburg), volume of oxygen required for combustion.....	25
chambers in Siemens recuperative system.....	49	pre-heating of.....	49
currents, maximum allowable velocities of in regenerative furnaces...	240	-producer, cooling of, omitted in hypothesis..	141
enriched, how obtained..	44	-producer, equation of reaction in.....	86
-fired furnaces, when economically substituted..	128		
-fired furnaces, improvements in.....	39		
-fired furnaces, recuperative organs in perfect, from one point of view..	69		
-fired furnaces (recuperative), selection of method for calculating efficiency of.....	67		

	PAGE		PAGE
Gas-producer, injection of hot products of combustion into.....	118	Göbbe, E.....	116
producer, office and delimitation of.....	40	furnace.....	99
-producer, office of in a furnace.....	40	Goutal formula.....	220, 221, 276
-producer, what it includes.....	40	Grate, problem of preservation of.....	127
-producer, Taylor.....	42	Grates, horizontal and inclined.....	43
-producers, how aided in operation by steam....	64	Gruner, calculation by.....	235
-producers, steam and other auxiliaries in... samples, method of taking in tests.....	60	rule, amendment to.....	248
Siemens.....	136		
Siemens, diagram showing theoretical temperature of formation of..	44	H	
specific heat of a, at any temperature, how determined.....	87	Harboard, F. W., cited.....	247
varying temperature of.....	11	Harvey.....	46, 95, 116
Gases, analysis of various industrial.....	98	Hearth conditions here taken as the same in all cases..	57
auxiliary to fuel gasification.....	46, 47	in furnaces.....	264
burned or oxidized, action of.....	64	in gas furnace.....	41
(or currents), classification of, in a complete gas furnace.....	58	recent modifications in..	49
influence of pre-heating... influence of the velocity of thermal capacities of between certain points, how expressed.....	41, 43	Heat balance-sheet of furnace, with double recuperation.....	93
thermal capacities of, per kilogram (table).....	3	balance-sheet, necessary factors of.....	130
thermal capacities of, per kilogram in Centigrade degrees (table).....	3	balance-sheet of a Siemens furnace, with double recuperation, fired with mixed gas, data required for.....	131
thermal capacities of, per molecular volume (table).....	11	of combustion and calorific power.....	7
thermal capacities of, per molecular volumes in absolute temperatures (table).....	13	efficiency of a furnace, study of.....	129
thermal capacities of, per molecular volumes in Centigrade degrees (table).....	12	latent, how affected by differences in gas-burning.....	62
thermal capacities and specific heats of.....	10	lost, definition of.....	55
used in firing furnaces....	47	lost in furnaces, knowledge of essential point.....	70
		lost, recuperation of.....	2
		lost and utilized in gas furnaces fired with mixed gas, double recuperation.....	105, 108
		lost and utilized in furnace fired with mixed gas, recuperation by secondary air.....	101
		lost and utilized in gas furnaces fired with mixed gas, triple recuperation.....	112
		lost and utilized in furnace fired with Siemens gas, with double recuperation.....	93



	PAGE		PAGE
Melting point of metals, apparatus for determining.	160	Parr standard calorimeter, directions for using.	209-213
Melting point of precious metals, wire method for determining.	161	Peclet, experiments by.	234
Metallurgy, books on.	304-305	formula by.	235
Metals, apparatus for determining melting and freezing points of.	160	Pennsylvania Steel Co.	246
precious, wire method for determining melting points of.	161	Pinzger, calculation by.	235
Moisture, determination of.	225	Platinum, determination of melting point of.	161
Molecular volume, definition of.	7	Ponsard furnace.	37
weight of fuel burned, computations in this work based on.	16	Ports, cross section of.	251
Morgan gas-producer.	44	in furnaces.	266
gravity-discharge billet-heating furnace.	100	Potash solution.	180
suspended-roof billet-heating furnace.	102	Producer blown by steam, reactions in.	61
Muffle furnace, calculation of the dimensions to be given to recuperative surfaces for.	252-254	grateless, advocated by Ebelmen.	96
N		-gas, calorific power of at 600°.	136
New Jersey Zinc Co.	191	-gas, method of finding temperature of combustion of.	18
Niclausse, M.	83	-gas (Siemens), temperature of combustion of when burned with preheated air.	23
boiler.	78, 80, 81, 83	-gas, volumetric analysis of.	134
multitubular boiler, front elevation of.	82	-gases, heat regeneration applicable to.	51
multitubular boiler, section through.	81	Producers without grates.	43
Nitrogen, determination of.	226	Pyrogallol, alkaline solution of.	180
O		Pyrometric cane for protecting wires of Le Chatelier thermo-electric pyrometer.	152
Oil, heavy, action of in gas-producer.	65	Pyrometer, Féry heat-radiation.	170, 171
Orsat apparatus for gas analysis.	178	heat-radiation.	171
Oxygen, absorption of.	184	Féry heat-radiation, lens type.	171
determination of.	227	Féry heat-radiation, mirror type.	172
P		Féry heat-radiation, mirror type, focusing device of.	172
Parallel counter-current system of recuperation.	238	Féry optical.	169
Parr calorimeter.	193	Holborn and Kurlbaum.	169
calorimeter, properties of.	207, 208	Le Chatelier thermo-electric.	147
		Morse.	169
		optical, of Le Chatelier.	168, 169
		principle of the thermo-electric.	150
		uses of.	153

	PAGE		PAGE
Pyrometer, Wanner.....	170	Recuperative chambers, useful surfaces of, should be adapted to exchange of calories.....	142
Pyrometers, registering, advantages of.....	153	efficiency defined.....	56
registering, where to place.	153	efficiency measure of relative value of a furnace.....	57
Pyrometry, books on.....	303-304	organs in gas-fired furnaces perfect from one point of view....., 69	
Q		system, Siemens.....	48
Queneau, A. L.....	46	Recuperators.....	47, 252
Queneau, A. L., system of....	113	Redtenbacher, formulas by...	234
R		Regeneration, carbon, no gain from.....	119
Radot furnace, G6bbe system..	86	Regenerators.....	47, 242
Radot-Lencauchez furnace....	99	proper dimensions for....	246
Record of the CO <sub>2</sub> contents of the stack gases from a hand-fired boiler.....	190	Regnault.....	11
Recuperation, adaptability of.	2	Regnault-Pfoundler formula...	203
double, by primary air and secondary air.....	108	Richards, J. W., cited.....	247
double, by secondary air and gas.....	102	Roofs in gas-fired reverberatory furnaces.....	49
as delimited in this work..	57	S	
double, primary and secondary air.....	94	Saillers producer.....	96
double, how best secured..	51	Sample-tube, manipulation of.	181
fundamental principles of.	65	Sampling in gas analysis.....	176
meaning of term in this book.....	53	Schoenwalders furnace.....	269
methods of.....	49	Schnabel-Gautier.....	47
organs (in gas furnace)..	40	Siemens, Frederick...37, 50, 110,	
by secondary air.....	99	120, 264	
by secondary air alone....	86	furnace.....94, 123, 124	
Siemens' invention of....	2	furnace, new.....110, 116, 120	
single adaptations of....	115	furnace, new, circulation of gas currents in.....	59
theory of.....3, 7		furnace, new, fallacies in regard to.....	59
by total air, advantage of.	111	furnace, new, with horse-shoe hearth.....	48-51
total, when impossible....	66	furnace, original, briefly described.....	37
triple, adapted to high temperatures.....	114	furnace, original, how improved.....	52
triple, alone may give complete recovery of calories	67	furnaces classified.....	92
triple, by primary air, secondary air and gas....	110	gas.....	123
triple, by primary air, secondary air and gas (Queneau system).....	113	gas defined.....	51
triple, worth serious consideration.....	110	gas, diagram showing theoretical temperature of formation of.....	87
without inversion.....	47	gas under given conditions, diagram showing temperature of combustion of.....	92
Recuperative chambers, neglect of the cooling of: hypotheses.....	142		

	PAGE		PAGE
Siemens gas, properties of.....	44	Temperature, high, and recu-	
glass tank furnace.....	99, 103-105	peration-- connection be-	
producer.....	94	tween.....	2
recuperative system.....	48	measuring for tests.....	134, 135
recuperator with inversion.	47	ruling, defined.....	54
siphon.....	46	ruling, and efficiency of	
siphon, drawbacks of.....	94	furnace, relation between	76
suggestions by.....	269	ruling, influence of.....	54
system, extension of to		influence of on the heat	
boiler firing unsuccessful	76	utilization in a fur-	
system of recuperation....	238	nace.....	53
William.....	37	ruling, invariableness of..	141
Siphon, Siemens.....	46	ruling, lack of in	
Société des Métaux.....	99	boilers.....	81
Spectrophotometer, König's...	170	Temperatures of about 1000°,	
Stafford, C. E.....	269	classification of furnaces	
Standardization, method of		for.....	128
Holborn and Day.....	150	of combustion.....	14
Steam as an aid in operation of		of combustion, general	
gas-producers.....	64	equation of.....	14
an auxiliary of recupera-		of furnaces, high.....	2
tion.....	63	high, production of.....	3
effect of use in furnaces..	63	low (as in steam boilers),	
for single recuperation,		have little to expect	
slight advantage of....	102	from gas recuperation..	128
Sulphur, determination of....	225	usual, given by furnaces	
Swindell gas-producer, with		with single recuperation,	
double face.....	62	fired by Siemens gas...	90
		Thermal capacity defined.....	10
T		Thermo-chemical reactions, ta-	
Table 12 (Goutal factors).....	222	ble of.....	8
13.....	287	-couple, apparatus for the	
14.....	288	protection of in roasting	
15, 16.....	289	kiln.....	154
17, 18.....	290	-couple, to replace injured	
19.....	291	one by new one.....	153
20.....	292	-couples, care of.....	153
21.....	293-295	-couples, diagram showing	
22.....	296-297	e. m. f. curves of dif-	
23.....	298	ferent.....	148
24.....	299	-couples, some types of...	149
Tar, action of in gas-producer..	65	Thermometer for experiments.	
Taylor gas-producer, water-		200, 201	
sealed, with Bild auto-		Thompson calorimeter.....	193
matic feed.....	60	Three-way cock, F, various	
gas-producer, with me-		positions of.....	181
chanical feed.....	42	cock, G, various positions	
grateless producer.....	43	of.....	182
producer.....	94	cock, H, various positions	
Temperature of combustion of		of.....	183
Siemens gas under given		Toldt, F., cited....	48, 240, 243,
conditions, diagram of.	92	244, 262, 265, 267, 268	
		Tubes, sample, used in gas an-	
		alysis.....	176

## V

	PAGE
Value, low thermal.....	220
Valve, Forter water-sealed re- versing.....	263
reversing.....	262
Wailes water-sealed.....	261
reversing.....	261
Vielle.....	7
Vigreux, C.....	46
Vivien formula.....	220
Volume, molecular, definition of.....	7

## W

Water gas, manufacture of....	45
gas, production of.....	97
gas, theoretical, tempera- ture of combustion of..	20

Water vapor, determination, how effected.....	177
vapor, dissociation of....	35
vapor in gases, apparatus for determination of...	177
Weights, atomic.....	7
molecular.....	7
Wellman tilting furnace.....	269, 270
Wire method.....	161
Wires, highly heated, life of during furnace tests....	150

## Z

Zinc, apparatus for determining the boiling point of....	158
furnace, parallel current re- cuperative.....	240
metallurgy, conditions pe- culiar to.....	245













17

D2

Mining  
dept.



121  
Somen

YC 33830

